ACTIVE POWER FILTER BASED ON INTERLEAVED BUCK CONVERTER

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Electrical Engineering

By

RAJASHREE BISWAS

Department of Electrical Engineering

National Institute of Technology

Rourkela

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Under the guidance of

Prof. A. K. PANDA

Department of Electrical Engineering

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CERTIFICATE

This is to certify that the thesis entitled "**ACTIVE POWER FILTER BASED ON INTERLEAVED BUCK CONVERTER**" submitted by Miss. **RAJASHREE BISWAS** bearing **Roll no 211EE2127** in partial fulfillment of the requirements for the award of Master of Technology Degree in Electrical Engineering at the National Institute of Technology, Rourkela is an authentic work carried out by her under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Prof. A.K. PANDA
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I cannot end without thanking my lovely family, on whose encouragement, support, and love, I have relied throughout my studies.

I would like to thank to all those who are directly or indirectly supported me in carrying out this thesis work successfully.

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Dedicated to my Parents, Sisters and Friends

CONTENTS

LIST OF ABBREVIATIONS

APF	Active power filter
IBC	Interleaved buck converter
APF-IBC	Active power filter based on interleaved buck converter
PPF	Passive power filter
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
HVDC	High voltage dc transmission
kV	kilovolt
MVA	megavolt ampere
MVAR	mega volt amps reactive
MW	megawatt
p.u.	Per unit
PCC	point of common coupling
PWM	Pulse Width Modulation
RMS	root mean square
VAR	Volt ampere reactive
THD	Total harmonic distortion
VSI	Voltage source inverter
FET	Field effect transistor
LPF	Low pass filter

LIST OF FIGURE

ABSTRACT

Power quality problem is a major problem now days. Causes of this problem can't be avoided but it can be mitigate. Active power filter (APF) plays a major role to improve the power quality. These active power filters mainly used are of voltage source type converters. Apart from all the advantages an active power filter it suffers from "shoot- through" phenomenon. Dead time is generally aided in firing pulses to avoid this phenomenon. This addition of dead time eliminates the "Shoot through" phenomena but it results in poor compensation performance.

A family of shunt active power filter based on interleaved buck converter (IBC) is explained in this thesis. This interleaved configuration based on the buck converter combination is advanced for its high frequency and high efficiency, in which the "shoot-through" is eliminated inherently without introducing the dead time.

In this thesis, the operation principle of active power filter based on buck switch cell is analyzed in detail. Features of interleaved buck cell are analyzed. "Shoot through" and dead time effect described briefly. Comparatively study of conventional method and half cycle modulated current controller is done. Corresponding control strategies are applied in bridge, full bridge, three-phase and three-phase four wire configuration. Simulation results are shown to verify the feasibility of the novel active power filter. This family of shunt APF used in the application with high reliability requirement and high compensation performance.

CHAPTER 1

1 INTRODUCTION

1.1 Introduction

1.2 Research background

1.3 Project motivation

1.4 Project objective

1.5 Chapter Summary

1.1 Introduction

Electrical energy is the most efficient and popular form of energy because it can be use easily at high efficiency and reasonable cost. The first electric network in the USA was established in 1882 and after that every corner of earth connected through these lines.

The modern society has come to depend heavily upon continuous and reliable availability of electricity. Computer and telecommunication networks, railway network banking, post office , life support system are few application that just cannot function without electricity whose life is thrown out of year, in case the electric supply is disrupted. Apart from that the industrial development totally depends upon the supply and quality of electricity

Both electric utilities and end users of electrical power are becoming increasingly concerned about the quality of electric power. The term *power quality* [1] has become one of the most prolific buzzword in the power industry since the late 1980s. The issue in electricity power sector delivery is not confined to only energy efficiency and environment but more importantly on quality and continuity of supply or power quality and supply quality. Electrical Power quality is the degree of any deviation from the nominal values of the voltage magnitude and frequency. Power quality may also be defined as the degree to which both the utilization and delivery of electric power affects the performance of electrical equipment. But now-a-days the quality of electricity is decreasing due to the nonlinear loads. Non-linear load generally denotes the power electronics and semi-conductor device application. This draws nonlinear current from the source. This is because they convert one form of electric energy to another form of electric energy and in these conversion lots of switching devices are used which makes the current discontinuous. Discontinuity of this current injects non-linearity in the supply current. This non-linear quantity contains harmonics and to eliminate this harmonics we required power filters. Active power filter plays a measure role in power quality improvement. Previously we are using passive filters to compensate the harmonic loss but now if also passive is used it is used with active filter. This combination of different types of filter is called hybrid filter. But in this thesis only active filter based on interleaved buck converter is analyzed in detail. Interleaved buck converter is a voltage source type converter; due to its simple structure and outstanding performance in compensation it is includes in active power filter work which is described later on.

Simple work of an active power filter is to inject the harmonics in to the supply which is out of phase of actual harmonics so as to cancel it. Fig1.1 gives the basic idea of the operation of the active power filter.

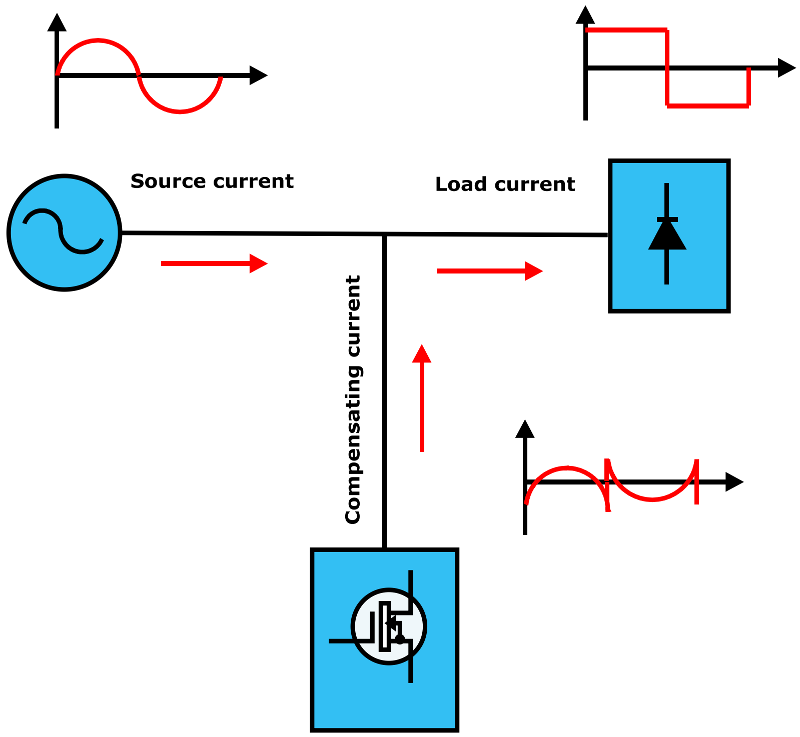


Fig. 1.1 Shunt active power filter

1.2 Research back ground

1.2.1 Power quality problem and IEEE standard

Reliable and clean electric power [1] is the demand of this modern society. Reliability means without interruption electricity must be provided and if there will be any then it must be repaired soon. Clean electric power means the voltage and currents are in phase and the wave shape of both the electrical quantity must be sinusoidal. Now these are the electric power condition at ideal case; but in reality it is different. Electric power suffers from many problems [2] some of those problems discussed below:

- Transients
- Impulse voltage
- Power system faults
- Improper grounding effect

- Distortion
- Flickering
- Harmonics

All of the above creates either sudden or slow disturbance in electrical supply or deteriorates the electric supply quality. All are important and plays major roles in power pollution but based upon this thesis work priority is given to harmonics. Harmonics makes the sinusoidal wave form to non sinusoidal. The detailed study is done in next section.

All electrical devices are prone to failure or malfunction when exposed to one or more power quality problems. The devices [1] may be a electric motor or a transformer, a generator, a computer, a printer, communication equipment or a house hold appliance. All these devices and other react adversely to power quality issues depending on the severity of problem.

Customer need to be protected from other customer producing excessive distortion on the supply and damaging equipment or causing inconvenient malfunctions. IEEE has several standards which address this problem.

The standard aspects of harmonics:

(i) The maximum level of harmonic voltage which are allowed on the supply,

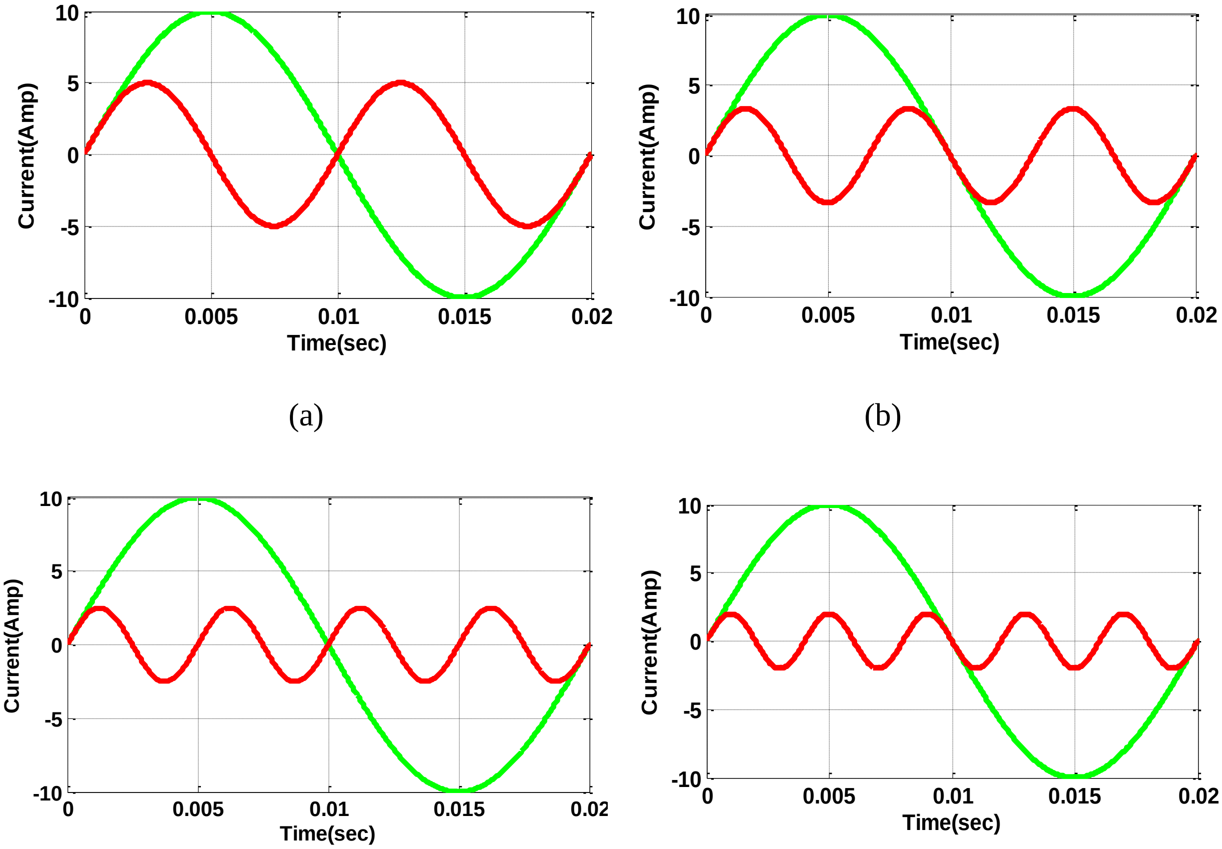
(ii) The maximum distorting current that household appliances can draw to ensure that levels in (i) are met,

(iii) The maximum distorting current that industrial installation can draw to ensure that the levels in (i) are met.

The present limit on harmonic voltages in the 415V supply system is 5% THD, 4% on odd harmonics and 2% on even harmonics [3].

1.2.2 Harmonic sources and effects

We can define harmonic [4] as the frequency which is integer multiple of the fundamental frequency (i.e 50 or 60 Hz). For example second harmonic is two time of fundamental (i.e 100 or 120 Hz), similarly for third harmonic it is thrice of the fundamental component (i.e 150 or 180 Hz) and so on. Fig 1.2 shows harmonics up to 5^{th} order with respect to the fundamental frequency.



(a) (b)

(c) (d)

Fig. 1.2 Fundamental component of the wave form with respect to different harmonics: (a) second order, (b) third order, (c) fourth order, (d) fifth order.

The French mathematician Jean Baptiste Joseph Fourier (1768–1830)[4], demonstrated that any periodic waveform can be deconstructed into a sinusoid at the fundamental frequency with a number of sinusoids at harmonic frequencies. Only a dc component may complete these purely sinusoidal terms. This concept can be explained by the following equation:

$$\begin{aligned} f(x) &= \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos nx + \sum_{n=1}^{\infty} b_n \sin nx \\ &= \frac{a_0}{2} + \sum_{n=1}^{\infty} c_n \sin(nx + \varphi_n) \end{aligned} \tag{1.1}$$

Where *f(x)* = General periodic wave form

a_0 = D.C component

a_n, b_n, c_n = Coefficient of the series

n= Integer number

$$a_0 = \frac{1}{\pi}\int_0^{2\pi} f(x)dx \quad a_n = \frac{1}{\pi}\int_0^{2\pi} f(x)\cos(nx)dx \quad b_n = \frac{1}{\pi}\int_0^{2\pi} f(x)\sin(nx)dx \tag{1.2}$$

$$c_n = \sqrt{a_n^2 + b_n^2} \quad \varphi_n = \tan^{-1}(\frac{a_n}{b_n}) \tag{1.3}$$

Electrical power system harmonic problems [1] are mainly due to the substantial increase of non-linear loads due to the technological advances such as the use of power electronic circuits and devices in ac/dc transmission links or loads in the control of power systems using power electronics.

In general, harmonic sources are given below:

- Converters, Devices which includes semi-conductor elements
- Generators, Motors, Transformers
- Lightening equipments working by gas discharge principle
- Photovoltaic systems, Computers, Electronic ballasts
- Uninterruptable power supplies, Switching power supplies
- Welding machines
- Control circuits
- Frequency converters
- Static VAR compensators
- Arc furnaces
- HVDC transmission systems
- Electrical Communication systems

Harmonic currents cause problems both on the supply system and within the installation. The effects [2] and the solutions are very different and need to be addressed separately; the measures that are appropriate to controlling the effects of harmonics within the installation may not necessarily reduce the distortion caused on the supply and vice versa.

There are several common problem areas caused by harmonics: -Problems caused by harmonic currents:

- overloading of neutrals
- overheating of transformers
- nuisance tripping of circuit breakers
- Skin effect

Problems caused by harmonic voltages:

- Voltage distortion in induction motors
- zero-crossing noise

1.2.3 Requirement of power filter

Increase in nonlinear load in power system leads to harmonic pollution [5]. This harmonic cases various disturbance, more losses and heating effects in drives. So it is required that something should be there which will reduce or suppress this harmonics. Power filters are used to resolve this problem.

These increase in harmonic current leads to distortion in voltage wave form, on-line induction motor temperature rise, excessive noise, vibration to actual damage, increasing in leakage current.

So as to minimize all this effects various types of compensator were introduced in power system such as, series shunt capacitor and inductor; one of that compensator is “power filter”.

1.2.4 Types of power filter

There are different types of power filter [7]; analyzing the current situation power filters widely classified into three categories, Fig 1.3 shows these category and sub categories of power filters.

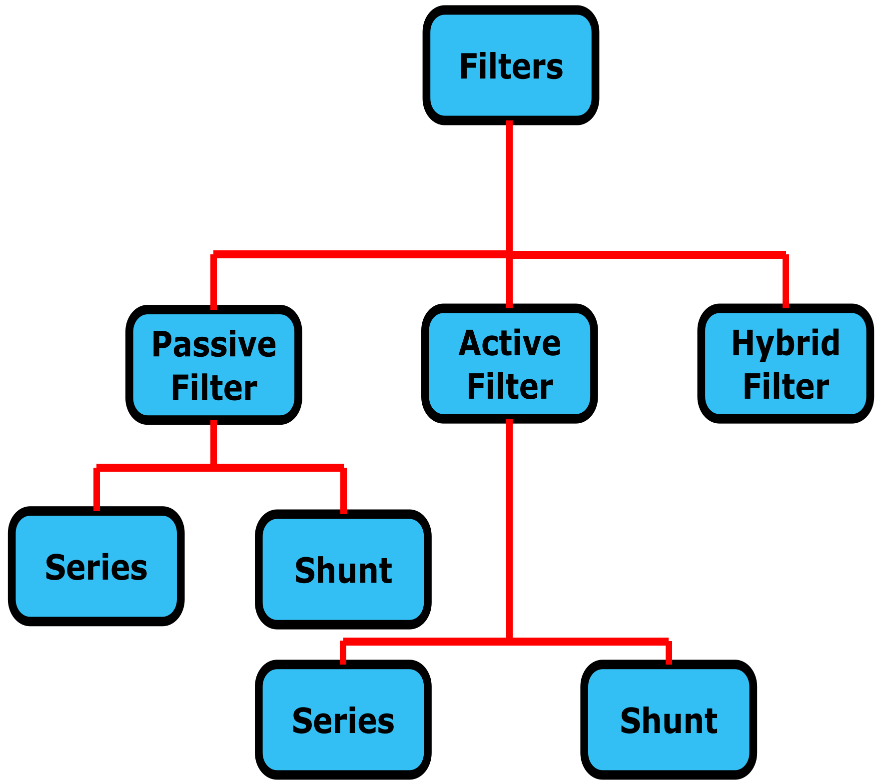


Fig. 1.3 Types of power filters

Harmonics are caused by harmonic-producing loads such as diode or thyristor converters and cyclo-converters, have been serious problems to solve. *Passive filters* [8] consisting of a bank of tuned LC filters and/or a high-pass filter have been broadly used to suppress harmonics because of a low initial cost and high efficiency. However, passive filters have the following disadvantages [9]:

(i) Filtering characteristics is affected by source impedance strongly.

(ii) Parallel resonance between a source and a passive filter causes amplification of harmonic currents on the source side at specific frequencies.

(iii) A passive filter may fall into series resonance with a source so that voltage distortion produces excessive harmonic currents flowing into the passive filter.

(iv) Limited to elimination of specific and fewer order of harmonics.

Shunt active power filter [10], [11] compensate current harmonics by injecting equal-but-opposite harmonic compensating current. The shunt active power filter operates as a current source injecting the harmonic components generated by the load but out of phase with the load current. This principle is applicable to any type of load considered a harmonic source. Apart from this with an appropriate control scheme the active power filter can also compensate the load power factor. The power distribution system sees the non linear load and the active power filter as an ideal resistor in this way.

It is well known that *series active power filters* [12] compensate current system distortion caused by non-linear loads by imposing a high impedance path to the current harmonics which forces the high frequency currents to flow through the LC passive filter connected in parallel to the load. High impedance which is imposed by the series active power filter is created by generating a voltage of the same frequency that the current harmonic component that needs to be eliminated. Voltage unbalance is corrected by compensating the fundamental frequency negative and zero sequence voltage components of the system.

Hybrid filters [13], [14] nothing but combination of series and shunt filter whether the filter may be active of passive. From its entire configuration active-passive configuration is more effective as it has advantages of both active and passive filters. Active power filters can be used with passive filters improving compensation characteristics of the passive filter, and avoiding the possibility of the generation of series or parallel resonance. One example of this combination is the series active power filter. In this scheme if the passive filters are not connected, the series active power filter can compensate only voltage regulation, and voltage unbalance. If passive filters are not used, the topology cannot compensate current harmonic components. This type of configuration is very convenient for compensation of high power medium voltage non linear loads, such as large power ac drives with cyclo-converters or high power medium voltage rectifiers for application in electro wining process or for compensation of arc furnace. In all these applications passive filters do not have enough compensation capability to reduce current harmonics in order to satisfy IEEE Std.519.

1.2.5 Interleaved buck converter in APF

Interleaved buck converter is nothing but combination of two buck converter whose inductor is placed one upon another and its is center trapped. In applications where non isolation, step-down conversion ratio, and high output current with low ripple are required, an interleaved buck converter (IBC) has received a lot of attention due to its simple structure and low control complexity [15]–[20].

Generally active power filter suffers from the phenomenon that is “shoot through” [21]-[23]. And in power electronics devices dead time [24]-[27] is generally added to the circuit so as to eliminate above phenomena. But at the same time it deteriorates the compensating performance of the active power filter. To improve the compensating performance external circuit is required which makes the Total circuit complex and hard to implement and cost effective. But introducing interleaved buck converter shoot through phenomena is eliminated without any other external control. The structure of interleaved buck converter is that type that it eliminates the shoot through effect automatically.

1.3 Project motivation

1.3.1 Harmonic pollution

Harmonics are sinusoidal voltages or currents with frequencies that are integer multiples of the supply frequency. These harmonics are generally caused by non-linear loads, such as equipment that has a capacitor and a diode type device a combination generally found in equipment with a switch mode power supply. Harmonics are generally at much higher levels in industrial or commercial premises that have variable speed drives or many computers. Inter-harmonics are voltages or current with frequency components that are not integer multiples of the supply frequency. Sources of inter-harmonics are heavy industrial equipment such as arcing devices, static frequency converters, induction furnaces, cyclo-converters and power-line-carrier signals are regarded as sources of inter-harmonics.

This pollution includes eddy current heating in equipment, Noise and torque oscillation in motors, Nuisance tripping of breakers and fuses , Telephone noise interference, Vibration or noise in panels, Metering errors ,Electronic equipment malfunctions ,Generator speed/frequency instability, Resonance causing large voltages, Data transfer errors & currents.

1.3.2 Increasing demand of active power filter

Because the incidence of harmonic-related problems in utility and industrial power systems is increasing, active power filters have attracted great attention and have been expected to be an effective remedy. Generally, an active filter has been considered to be a current source connected in parallel with the load (harmonic source). The approach is based on the principle of injecting harmonic current into the ac system, and the amplitude is same and reverse phase to that of the load current harmonics. It has been wrongly believed that the active filter is an ideal harmonic compensator whose compensation characteristics would not be influenced by the source impedance**.**

1.3.3 Single switch leg based inverter

Single switch leg based inverter is a special type inverter topology which receives more and more research since its proposal in [28]. It works as the combination of dc-dc converter with parallel connection. Its unique characteristic is high reliability and robustness, introducing this topology into APF application could increase the reliability of the APF equipment [29-31].

1.3.4 Advantages of interleaves structure

Interleaved buck half bridge active power filter is based on the analysis of the dual-switch inverter. Principle of operation and control strategy of the novel APF is simple. Generation law of the interleaved buck converter (IBC) is based on the comparative analysis of traditional three-terminal switch cell.

Apart from this the simple structure of interleaved structure eliminates "shoot through" phenomena and requirement of dead time [32]. It reduces cost and complexity of the circuit in practical application.

1.4 Project objective

- To overcome "shoot through phenomena" and "dead time" in active power filter with interleaved buck converter.
- To analyze the interleaved buck converter; its operating principles and features.
- To study Half-cycle-modulated current modulation technique in comparison with the conventional current control method
- To implement this modulation technique to half bridge, full bridge, three phase and three phase four wire buck converter based active filter
- To study *p-q* method and i_d-i_q method in three phase and three phase four wire system
- To implement this method in various configuration of three phase active power filter

based on interleaved buck converter

- To analyze how this technique is better than others in terms of reliability and efficiency
- To Simulate all the configuration of active power filter based on interleaved buck converter
- To compare THD of source current in all the configuration with the case of no compensation

1.5 Chapter summary

In this chapter various aspects of power system problems are discussed. Problem caused by harmonics its effects on electrical devices is discussed. Resolution of this problem and requirement of power filters is analyzed. Various types of passive, active, hybrid filters are discussed. Project motivation and objective of project is explained in this chapter.

CHAPTER-2

2 ACTIVE POWER FILTER BASED ON INTERLEAVED BUCK CONVERTER

2.1 Introduction to buck switch cell

2.2 Shoot through and dead time effect

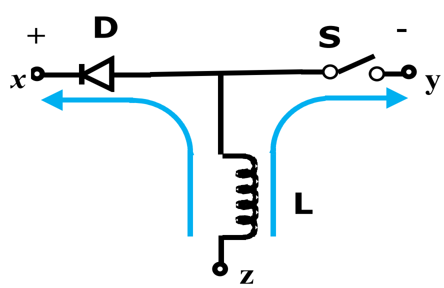
2.3 Elimination of this effect

2.4 System description of active power filter

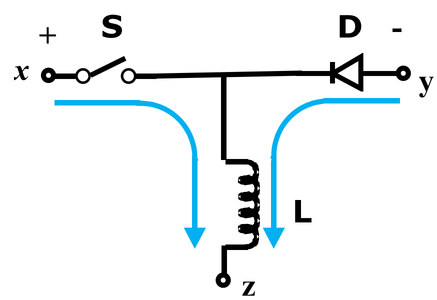
2.5 Chapter summary

2.1 Introduction to buck switch cell

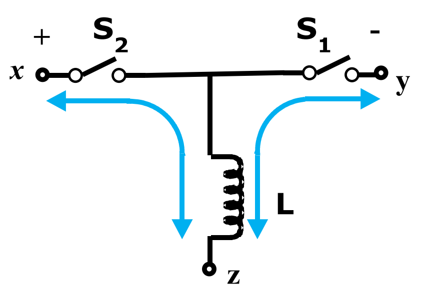
Traditional dc/dc, dc/ac/dc and ac/dc power converter are based on the basic three terminal cells which are given in Fig. 2.1. In the switch cell A and B, which is composed with a diode D a bidirectional switch S and inductor L, only a unipolar power could be transmitted as shown in Fig. 2.1(a) and (b). Therefore, the switch cell A and B are usually used in the DC/DC converter such as buck, boost and buck-boost. In order to transmit the bipolar power, diodes in these two cells could be replaced as a bidirectional power switches as shown in Fig. 2.1 (c).



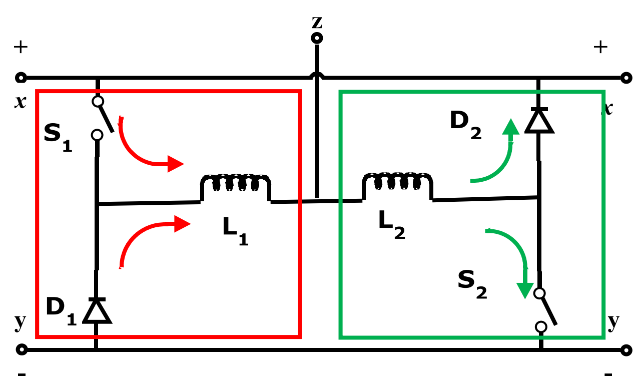
(a) Switch cell A



(b) Switch cell b



(b) Switch cell C



(d) Novel switch

Fig. 2.1 Traditional switch cell and interleaved buck switch cell

This switch cell based on the two bidirectional switches S_1 and S_2 is the basic cell of ac/dc and dc/ac converter. In order to avoid the short connection of the “+” and “-” dc bus, terminal y will not connect with the “+” bus, and the “shoot-through” that S_1 and S_2 switches on simultaneously must be avoided in the ac/dc and dc/ac application.

From above analysis, in order to achieve ac power conversion, bidirectional power should flow between the terminal x and terminal z and between terminal y and terminal z. Meanwhile, in the two switches based traditional bridge leg, dead-time should be added to the drive signals to avoid the bidirectional power flows between terminal x and y.

Considering the “dual” behavior of power flows between terminal x & z and terminal y & z in switch cell A and B, novel interleaved buck switch cell will be obtained by combination of these two traditional switch cell as shown in Fig. 2.1(d). Same terminal in Fig. 2.1(a) and (b) will be connected directly, and switch cell A and switch cell B become one sub cell of the IB switch cell, sharing the bidirectional power flows in IB switch cell, as shown in Fig 2.1(d). So, the power converter based on the novel switch cell will achieve better performance.

2.2 Shoot through and dead time effect

Shoot through is defined as both the upper switch and lower switch of the same leg being turned on at the same time. In Fig. 2.2 a normal converter with four switches S_1, S_2, S_3, S_4 are shown. In ideal operation S_1, S_2 operates for positive half cycle and S_3, S_4 operates for negative half cycle. But some time before switching off of S_1 and S_2, S_3 and S_4 switched on which creates a short circuit along the dc link voltage as shown in Fig. 2.2. This short circuit causes “shoot through” phenomena in voltage source converters.

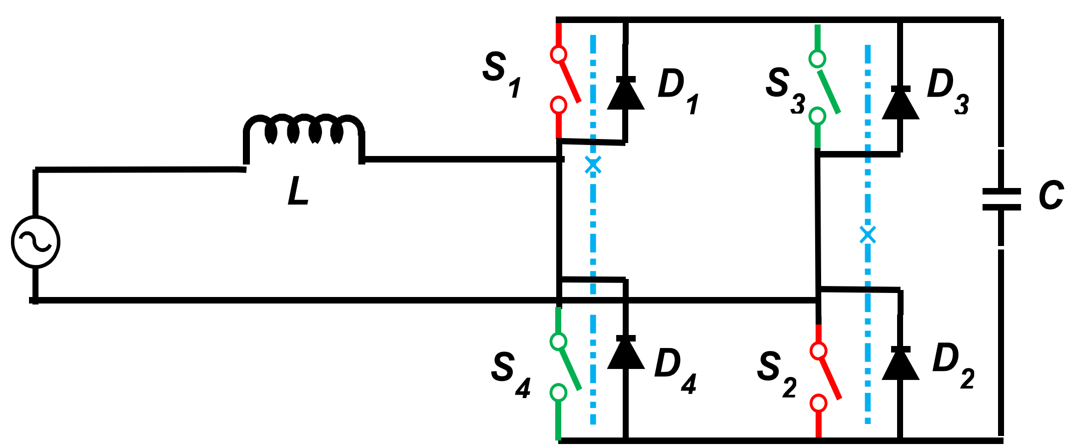


Fig. 2.2 Conventional converter based APF

It leads to sudden rise of current for a short period of time i.e. in micro seconds. Shoot through will cause additional power dissipation in the switching device, but does not lead to device failure in FETs of contemporary design. But in some severe cases it leads to failure of the device also. Shoot through induced losses will probably be greatest at light load. In terms of the overall system design, a design with some shoot through may actually have better efficiency than another with a different set of devices and no shoot through. A typical cause of shoot through is high *dv/dt* at the switch node causing the low side gate to rise. Another cause can be driver timing and circuit layout leading to overlap upper switch turn off and lower switch turn on; at that time a short circuit will occur along the source voltage side which leads to sudden current which is several time of the actual current. For one time it will not cause any failure but for long period of time it can permanently damage or increase the loss level.

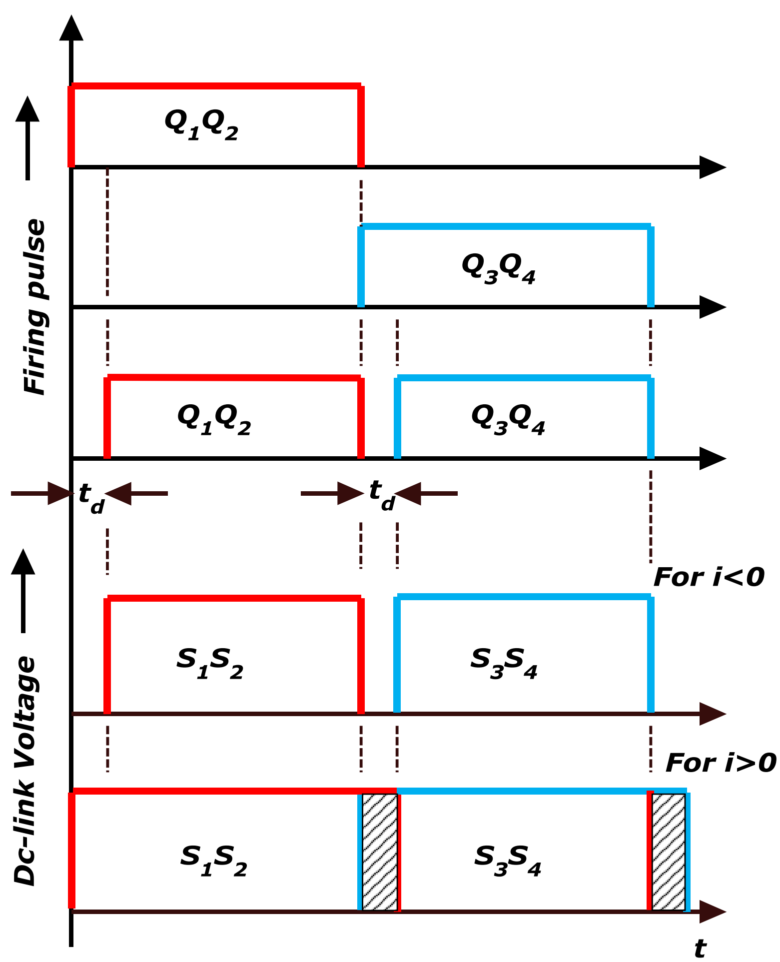


Fig. 2.3 Pulses with dead time and effect of dead time

To avoid "shoot-through" in VSI, *dead-time* should be added to the drive signals. However, the dead-time control will introduce an error into the output voltage of VSI so that the accuracy of APF current is affected and compensation effect will be decreased. Fig. 2.2 shows the leg of single phase PWM converter. The PWM control signal drives the transistors through the time delay circuit. The drive signals Q_1, Q_2, Q_3, Q_4 for the switches S_1, S_2, S_3, S_4 respectively. In Fig. 2.3 the pulses with delay time t_d is shown.

During the delay time, all switches are ceased to conduct, and the output terminal across dc-link seems to be floating. However, if the circuit current i is continuous, as is normally the case, the current then flows through the freewheeling diodes present with each of the switch. Which one of the diodes will conduct depends on the direction of the current flow. When the current i is negative dc link voltage becomes pulsating and when current i is positive an overlapping condition arises which is shown by hashed line. Obviously, during the delay time, the dc-link voltage cannot be controlled by drive signals but is determined by the current condition, that is, the direction of the current flow. Thus, the voltage deviation makes the magnitude of the current be smaller than expected. This in turn implies one of the important effects of the time delay; the decrease in the effective output voltage of the converter. This in turn affects the compensating performance of active power filter.

Large numbers of researches have been done to overcome dead-time effects introduce kinds of complex compensators to compensate the dead-time effect and achieve good theoretical effects. But the effects in practical applications will be not so good because of the delay of the drive circuits, characteristics of power devices and influence of working environments. Furthermore, this kind of method cannot avoid the possibility of "shoot-through" radically.

2.3 System description of active power filter

Fig. 2.4 Illustrate the system diagram of half bridge IB- APF.As all active power filters the main aim of this active power filter is to mitigate the harmonics. Only difference is that instead of using a normal voltage source converter here interleaved buck converter is used. The diagram shows that it is a shunt active filter and it injects current to the source line in order to achieve the harmonic demand of the load side.

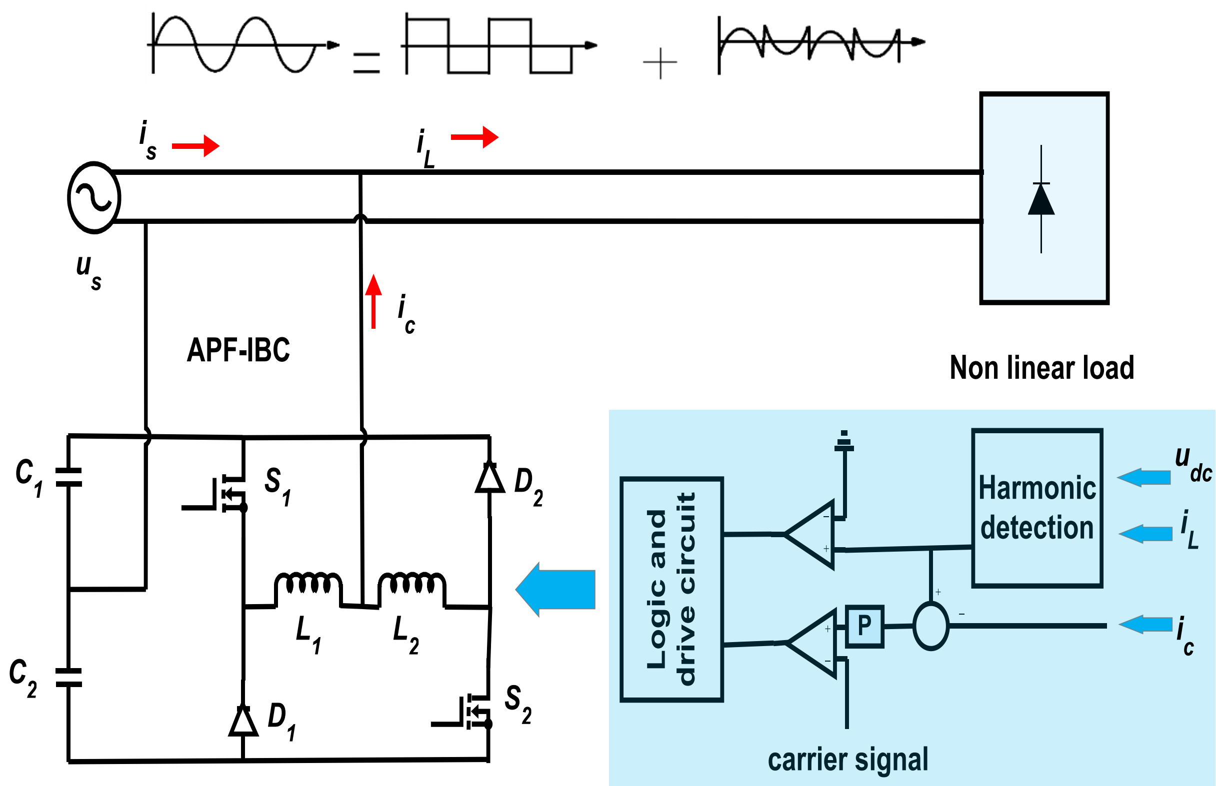


Fig. 2.4 System diagram of half bridge interleaved buck topology based active power filter (APF based on IBC)

In the control strategy, the detected load current and dc side voltage are sent to the harmonic detection unit to get the compensation current reference and maintain the balance stability of dc-link voltage. Logic and drive circuit provides the sequence of signal for both upper and lower switch of the interleaved buck converter and results in good compensating performance.

2.3.1 Half bridge topology

Here, the bridge leg is based on series connection one switch (S_1, S_2) and one diode (D_1, D_2). APF connects with the power grid at the middle point of half bridge split-capacitor (C_1 and C_2) and the middle point of series connected inductor (L_1 and L_2) as in Fig. 2.4. We can see from the figure that one leg of a simple VSI is converted to half bridge configuration. The mid-point split inductor are used in between the switch and the free-wheeling diodes.

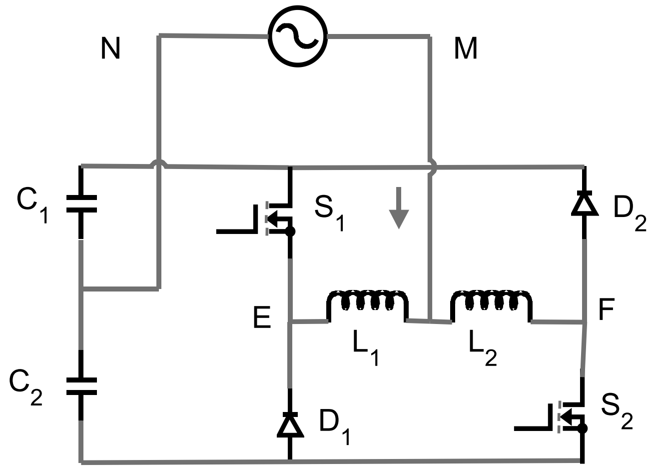


Fig. 2.5 Half bridge configuration of APF-IBC

A major advantage of half bridge configuration is it reduces the controlled switch cost and at the same time it eliminates the shoot through phenomena without the use of dead time. So it emerges into an APF with less cost, high reliability and better compensating performance.

2.3.2 Full bridge topology

Full bridge concept will be derived upon the combination of two half bridge IB switch cell and full bridge configuration is given by Fig.2.5. Two interleaved buck cells are defined as cell I and cell II. Cell I is composed of power switches $S_1$and S_2, power diodes *D1*and *D2*, inductors *L1*and *L2*. Cell II is composed of power switches S3and S4, power diodes D3and D4, inductors L3and *L4*. *C* is the APF DC capacitor and voltage across it is DC-link voltage.

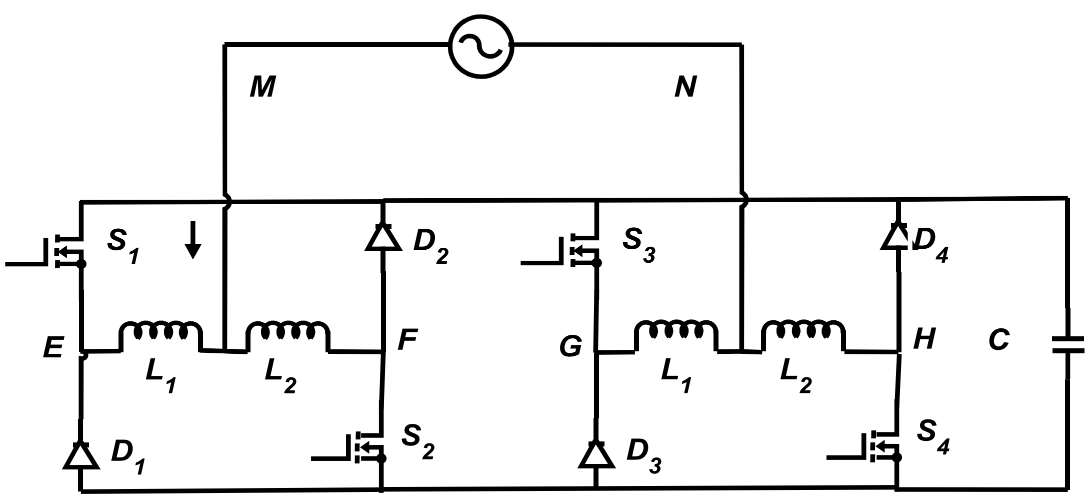


Fig. 2.6 Full bridge configuration of APF-IBC

In this topology, the dc voltage utilization increased, compared with the half bridge topology. In case of half bridge and full bridge both have same dc-link voltage where full bridge APF-IBC has more no of switch and components. Mean while, reduced cost and power loss and simple control for the dc link capacitor voltage benefits the capability and better compensation performance.

2.4 Chapter summary

This chapter deals with a deep look through interleaved configuration. “Shoot through” phenomenon and dead time effect is explained with the help of proper diagrams. Buck switch cell is analyzed with the example of different switching strategies. Half bridge APF-IBC along with each segment is described briefly. Half bridge and full bridge interleaved topology with their features are explained.

CHAPTER-3

3 CONTROL STRATEGY

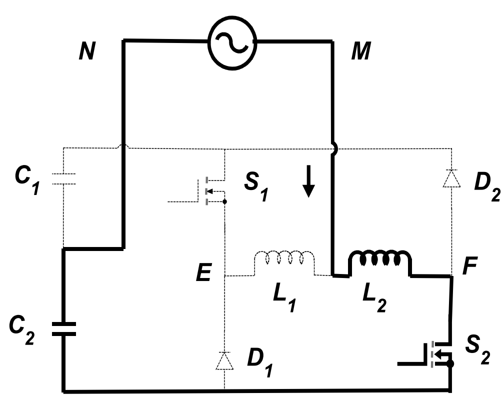
3.1 Introduction

Control of a system based on active power filter denotes the close loop operation of the system; it comprises of the elimination of errors in dc-link voltage control and generation of the switching frequency for the active power filter switches. Actually the main aim of the control strategy is to change the shape and value of compensating current as required; for that we have to control the switching frequency. It again depends on the reference compensating current value because it is the actual value of the harmonic content that the nonlinear load draws from the source. The result of the operation of control system of an APF-IBC is harmonic free sinusoidal source current which is desired.

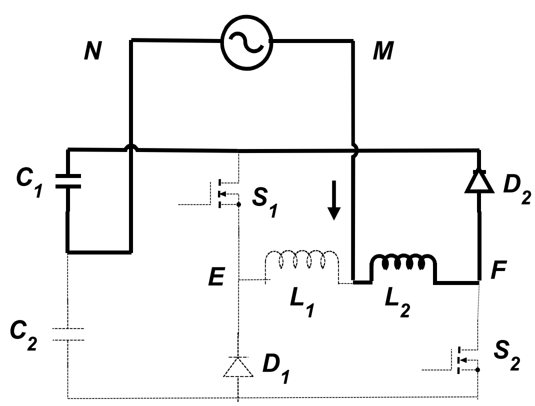
3.2 Operating principle

The operation principle of APF-IBC is mainly depends upon the half cycle modulated current control. In this control method the variable frequency modulation is adopted. This variable frequency modulation is done by taking triangle wave as carrier wave. A detail of this is described in next section.

According to this control when compensating current is positive during positive half cycle; switch S_2 is switched and C_2 supplies power when the rate of change of the compensating current is greater than zero. When the rate of change of compensating current is less than zero D_2 conducts and C_1 is in its charging mode. Fig: 3.1(a), (b) shows the two stages.



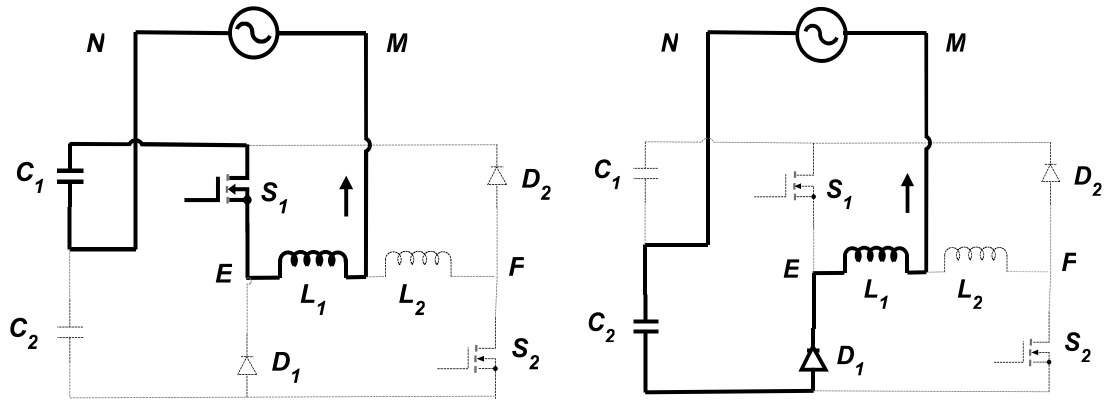
(a)



(b)

Fig. 3.1 Operation stage of half bridge IB-APF for positive half cycle

Similarly for the negative half cycle when rate of change of the compensating current is greater than zero, switch S_1 switched on and C_1 supplies power. When the rate of change of compensating current is less than zero D_1 conducts and C_2 is in charging mode. Fig: 3.2 (a), (b) sh**ow**s the two stages.



(a) (b)

Fig. 3.2 Operation stage of half bridge IB-APF for negative half cycle

We can observe from the above stages that at a time instant one switch is conducting the current. When S_1 is on other three switches S_2, D_1, D_2 are not working. Similarly for the other three cases. Which demonstrate that there is no chance of "shoot through" phenomena as at a time no two switching devices were operating.

3.3 Harmonic detection technique

Fig. 2.4 gives the schematic idea of the harmonic detection block; dc link voltage and load current are input to the block and reference current is the output. Fig. 3.3 gives the internal circuit of the harmonic detection block.

Shunt active power filters have been employed in order to eliminate current harmonics and to compensate reactive power. Dc-link voltage of the filter should be controlled in order to supply the power losses of filter on the grid, providing that more effective filtering and reactive power compensation are obtained. So to obtain constant performance dc- link voltage should be constant. The error signal of dc link voltage and reference voltage is given to the PI controller. The main work of PI controller is to minimize the error and to make the dc link voltage constant

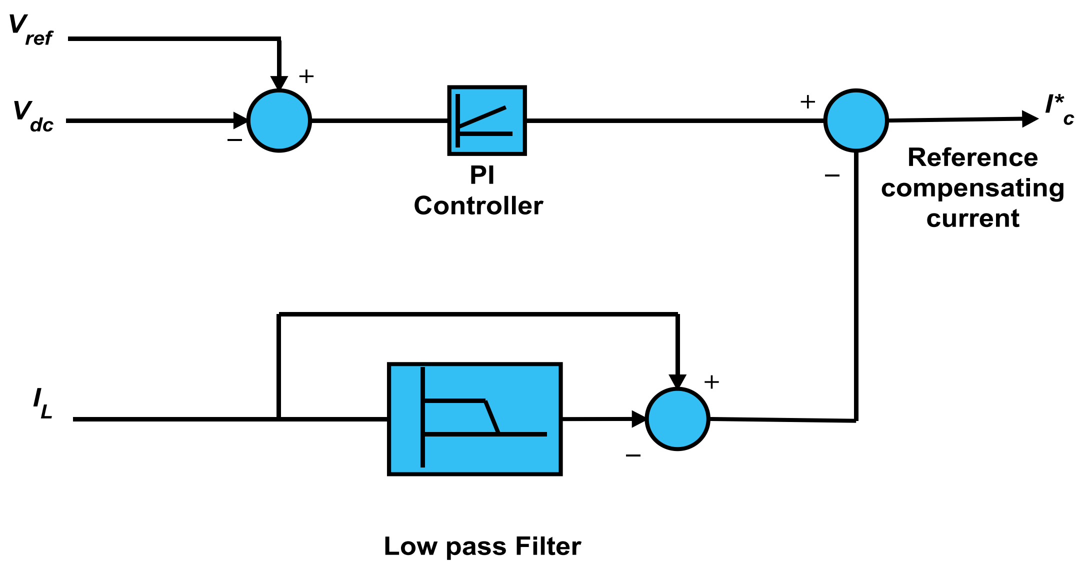


Fig. 3.3 Harmonic detection block of active power filter based on interleaved buck converter

Harmonics are present in load current. The fundamental component of load current is the source current; compensating current is the difference between the source current and the load current. That's why load current is passed through the low pass filter to filter out the fundamental current. This fundamental load current subtracted from the actual load current which gives the harmonic current. The filter is taken here is fourth order low pass Butterworth filter. The cut off frequency is taken simply the fundamental frequency so as to pass the fundamental component of load current. Harmonic current is then inserted into the voltage control circuit. By comparing the output of PI controller and harmonic current reference compensating current is generated.

This harmonic detection algorithm works for half bridge as well as full bridge. Full bridge interleaved buck converter is parallel combination two half bridge converter. Only difference is that it requires less dc-link voltage. The load current and the total control strategy remain same.

3.4 Modulation method and logic circuit

To achieve the switching performance as described in section 3.2 half cycle modulated current control is adopted. The error signal of actual compensating current and the reference compensating current is modulated based on triangle wave modulation technique.

Hysteresis current control is not adopted because at variable switching frequency the switching ripple current not easily filtered, introducing the switching noise to the power grid.

Moreover, the variable switching frequency will make the power switch uncontrolled in the large power application.

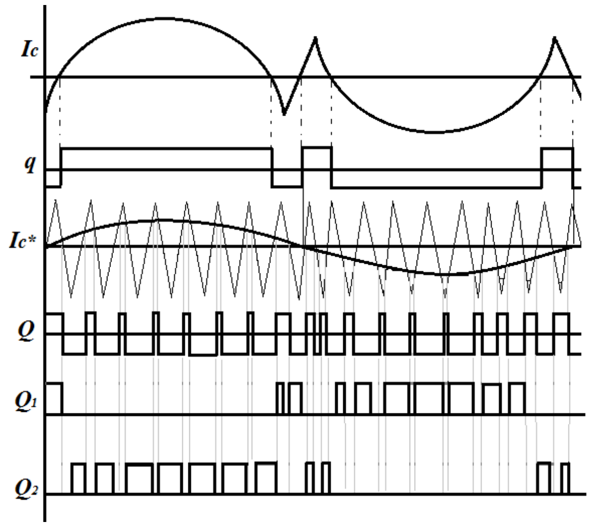


Fig. 3.4 Modulation method for IB-APF

Fig: 3.4 Illustrates the modulation methodology. The high frequency control signal is obtained by modulation of the output of current controller and carrier wave. The low frequency control signal is obtained from zero crossing detection of the reference compensation signal.

The final drive signal Q_1 and Q_2 will be obtained with Q and low-frequency polarity signal q. Q_2 will be obtained by using “and” operation of Q and q; and Q_1 will be obtained by using “and” operation of invert signal of q and Q. As shown in Fig. 3.5 this operation is done by the logic and drive circuit.

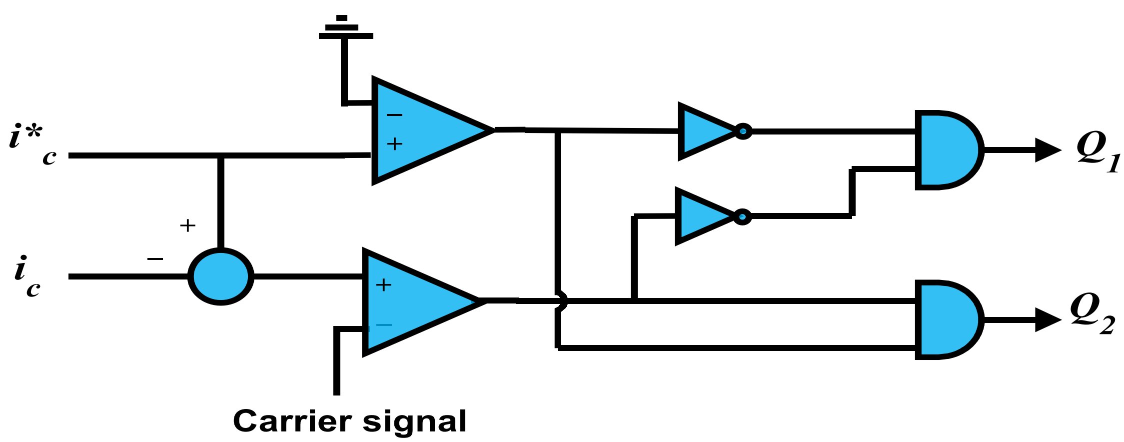


Fig. 3.5 Logic circuit

3.5 Comparison with conventional control strategy

The used modulation method is different from the conventional method because the switching is not given in continuous manner. It is totally depends upon depends upon the reference compensating current. Fig. 3.6 illustrates the conventional modulation methodology.

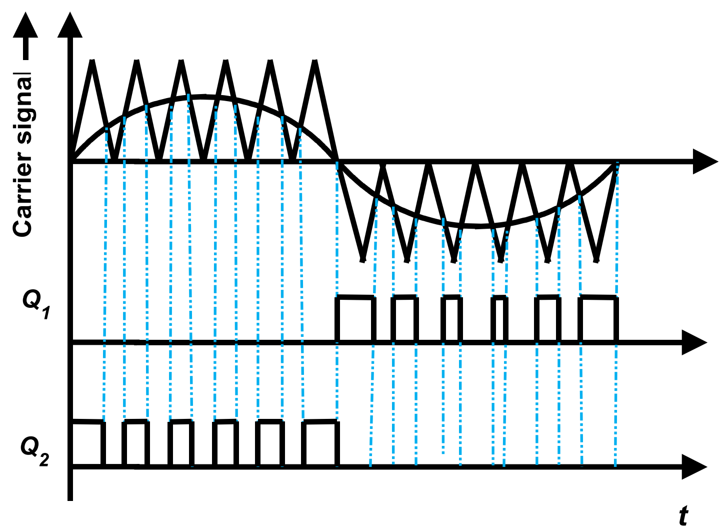


Fig. 3.6 Conventional modulation method

From the above figure we can see that we are simply modulating the error signal to obtain the switching frequency Q1 and Q2. Comparison of the conventional switching frequency and the half cycle modulated current control method is given in Fig. 3.7.

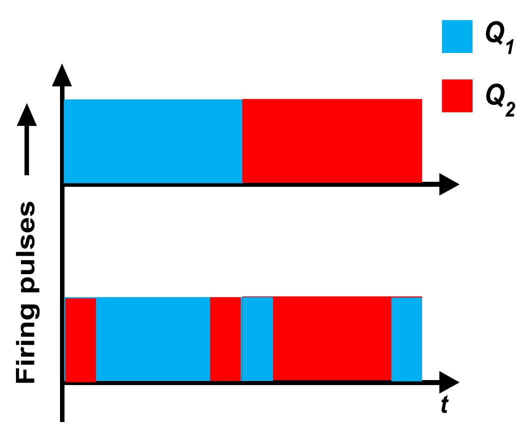
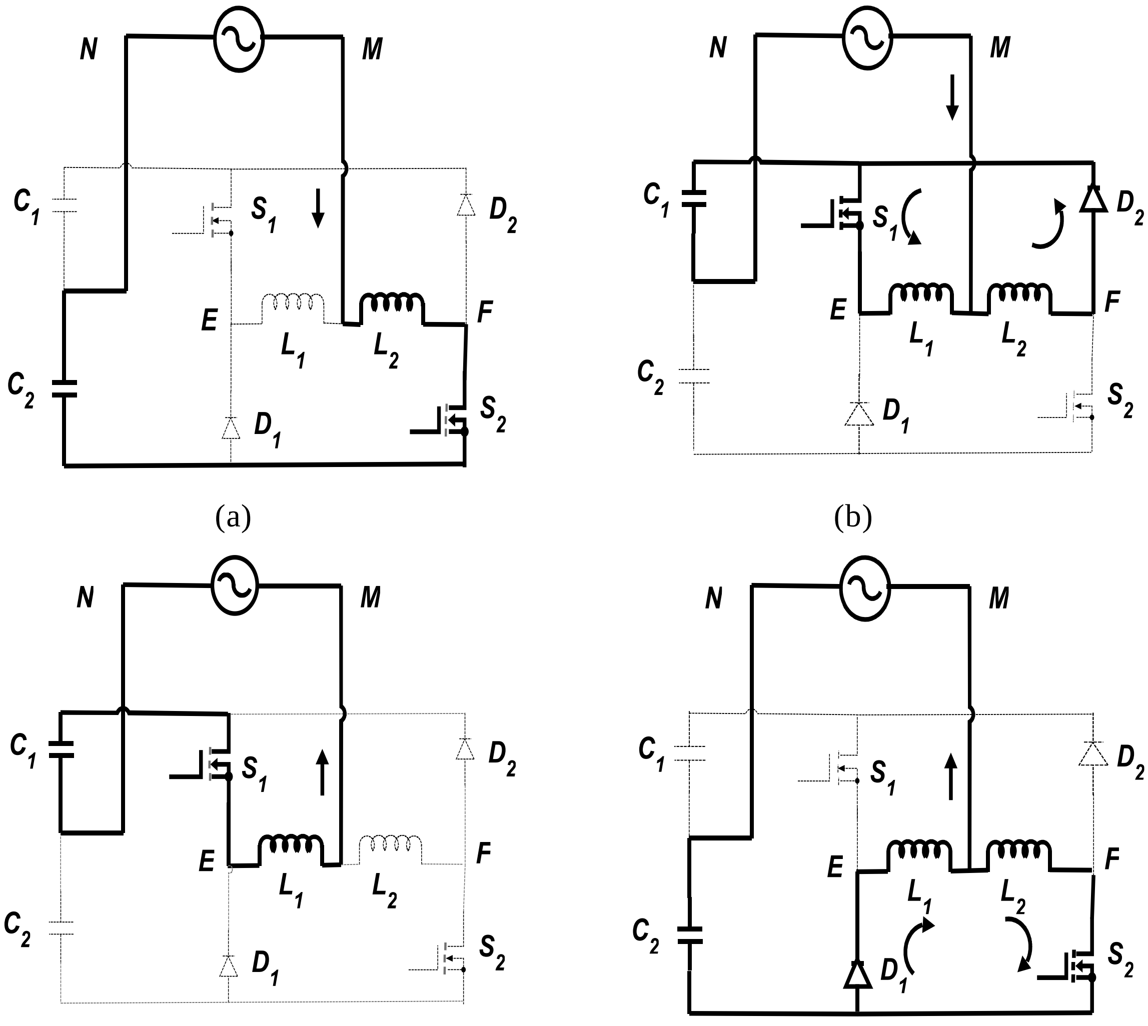


Fig. 3.7 Comparison between conventional and proposed method

From the above figure it can be seen that in conventional method during positive half cycle Q_2 operates and during the negative half cycle Q_1 operates. It leads to shoot through phenomena as simultaneously S_2 and D_2 starts conducting as shown in fig. 3.8



(a) (b)

(b) (d)

Fig. 3.8 Stages of half bridge topology of APF-IBC with conventional modulation method

The analysis before points out that the interleaved buck cell consist of two unidirectional power units and each of them is in charge of the flowing of the unipolar current. So the reasonable control strategy is each unit dealing with the half wave current of its own. That is when the compensating current is positive, lower cell works while upper cell has no current flowing through; on the contrary, when the compensating current is negative, upper cell works and there is no current flowing through lower cell.

Compared with the conventional phase control as shown in Fig. 3.8 the control process described as follows: when the lower switch is on, the initial current stage I shown as in Fig. 3.8(a). When the lower switch is off the current through the inductor L_1 is not zero and it will flow through the upper diode D_1. At the same time the upper switch S_1 is also switched on as a result a loop current will flow through the upper loop as shown in Fig. 3.8(b). This current flows through S_1, L_1, L_2, D_2 which is undesirable and leads to "shoot through" phenomenon. Same happens for the lower loop also as shown in Fig. 3.8(c), (d). But the stages with the half cycle modulated current control as shown in Fig 3.2, 3.3 there is no such loop current so no "shoot through" phenomena.

3.6 Chapter summary

This chapter describes the total close loop control used for the project. It includes voltage control; which is based upon PI controller, current control i.e. generation of switching pulses for single phase APF-IBC. A comparative study of the conventional control strategy and half cycle modulated control strategy has been done. It has been proved theoretically that half cycle modulated control strategy gives better compensation compare to the conventional one.

CHAPTER- 4

4 APLLICATION OF APF-IBC TO THREE PHASE SYSTEM

4.1 Harmonic mitigation in three phase system

4.1.1 Introduction

Some time it is mistaken that three-phase system is combination of three separate single phase system; but in reality three phase system is different from three combined single phase circuit.

Simply the load current in single phase system is square wave but in case of three phase system it is quasi square wave. There are other issues are there in terms of circulating current, zero sequence current, neutral current which are not present in a single phase system.

In case of an active filter also the control strategy is different from the single phase active power filter. Mainly the harmonic detection part is different from the single phase filter. There are several methods of harmonic detection. We can do it for separate phases also but the total control circuit will be complex. Because it will require more filters and separate control circuit. So from all methods two methods attains popularity due to its outstanding results. They are *p-q* method and i_d-i_q method explained in next section.

4.1.2 *p-q* method

The *p-q* theory [33] is based on a set of instantaneous powers defined in the time domain. No restriction were imposed on the voltage or current wave forms and it can be applied to three-phase systems with or without neutral wire for three phase voltage and current wave forms. Thus, it is not only in the steady state, but also in transient state. Other traditional concepts of power are characterized by treating a three-phase system as three single-phase circuits. The *p-q* theory first transforms voltage and current from the *abc* to *αβ0* coordinates, and then defines instantaneous power on these coordinates. So this theory always considers the three-phase system as a unit system; not a superposition or sum of three single-phase circuits.

The *p-q* theory uses the *αβ0* transformation also known as the Clarke transformation [33], which consists of a real matrix that transforms three-phase voltages and currents into the *αβ0* stationary frames.

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{4.1}$$

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{4.2}$$

The inverse transformation is as fallow

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \tag{4.3}$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} \tag{4.4}$$

The instantaneous active and reactive power are defined by

$$\begin{bmatrix} p \\ q \\ p_0 \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta & o \\ v_\beta & -v_\alpha & o \\ o & o & v_0 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} \tag{4.5}$$

Which can be decomposed into oscillatory and average terms $p = \tilde{p} + P$, and $q = \tilde{q} + Q$. Under balanced and sinusoidal mains voltage conditions the average power components are related to the first harmonic current of positive sequence, i_{ih}^{+} and the oscillatory components represent all higher order current harmonics including the first harmonic current of negative sequence, $i_{nh}^{+} + i_{1h}^{-}$. Thus, the APF should compensate the oscillatory power components so that the average power components remain in the mains. In this way the power rating of the APF is minimum. After eliminating the average power components by low-pass filters (LPF) the powers to be compensated are $p_c = -\tilde{p}$ and $q_c = -\tilde{q}$.

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p_c \\ q_c \end{bmatrix} \tag{4.6}$$

The reference compensation currents are obtained by inverting the equation (4.6) and it is converted to three phase by equation (4.3)

4.1.3 i_d-i_q method

In electrical engineering direct-quadrature transformation is a mathematical transformation used to simplify the analysis of three-phase circuits. For balanced three-phase circuits application of the *dqo* transform reduces the three AC quantities to two DC quantities obviously in terms of current. Simplified calculations can then be carried out on these imaginary DC quantities before performing the inverse transform to recover the actual three-phase AC results. Again it is often used in order to simplify the analysis of three-phase synchronous machines or to simplify calculations for the control of three-phase inverters.

Formula for *abc* to *dq* transformation

$$\begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} sin(\omega t) & sin(\omega t - \frac{2\pi}{3}) & sin(\omega t + \frac{2\pi}{3}) \\ cos(\omega t) & cos(\omega t - \frac{2\pi}{3}) & cos(\omega t + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{4.7}$$

Formula for *dq* to *abc* transformation

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} sin(\omega t) & cos(\omega t) & 1 \\ sin(\omega t - \frac{2\pi}{3}) & cos(\omega t - \frac{2\pi}{3}) & 1 \\ sin(\omega t + \frac{2\pi}{3}) & cos(\omega t + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_o \end{bmatrix} \tag{4.8}$$

Above equation gives the idea about three-phase and three-phase four wire system only in case of three phase four wire system zero sequence component is there which is not present in the case of a three phase three wire system.

For detection of harmonics instantaneous active and reactive load currents and can also be decomposed into oscillatory and average terms $i_d = \tilde{i} + I_d$ and $i_q = \tilde{i} + I_q$. The first harmonic current of positive sequence is transformed to dc quantities, i^{+}_{dq1h} , i.e., this constitutes the average current components. All higher order current harmonics including the first harmonic current of negative sequence, $i^{+}_{dqnh} + i^{-}_{dq1h}$, are transformed to non-dc quantities and undergo a frequency shift in the spectra and so constitute the oscillatory current components. These assumptions are valid under balanced and sinusoidal mains voltage conditions.

Eliminating the average current components by LPF's the currents that should be compensated are obtained and reference compensating current is obtained with the help of transformation in equation (4.8).

4.2 Three phase APF based on IBC

4.2.1 System description

The interleaved buck topology can be implemented to three phase circuit also. The schematic block diagram is shown in Fig. 4.1. It consist of two transformation block which transforms three phase to two phase and again two phase to three phase quantity. In this project work two transformation methods were adopted they are *p-q* transformation and i_d-i_q transformation. The difference between two methods was discussed in section 4.1.

One of the characteristics of both methods is that the compensating currents are calculated directly from the mains voltages enabling the methods to be frequency-independent. Use of a PLL is avoided and a large frequency operating range can be achieved limited chiefly by the cutoff frequency of the current control system. Furthermore, under unbalanced and non sinusoidal mains voltage conditions, a large number of synchronization problems are avoided especially if a PLL is synthesized with a fast dynamic response.

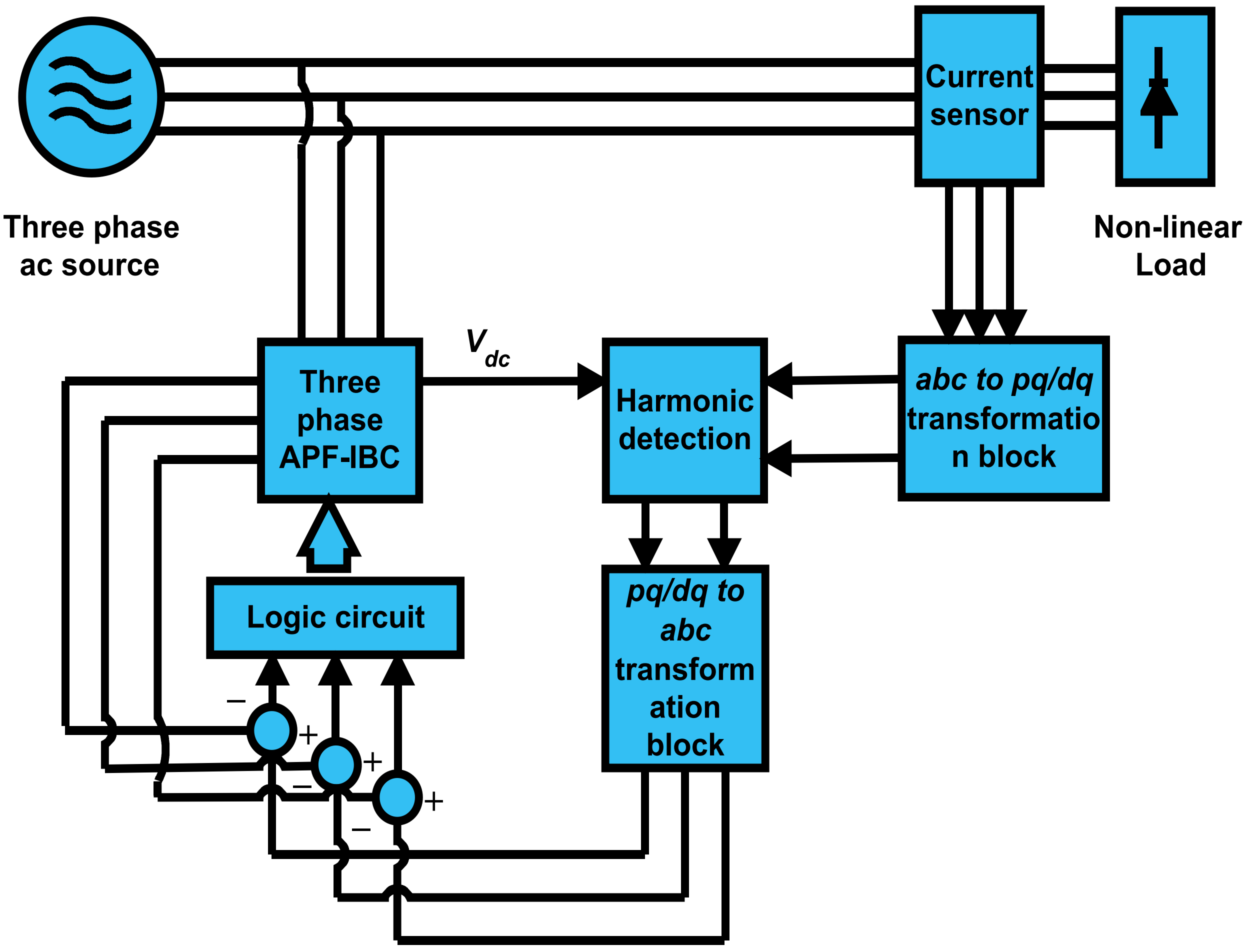


Fig. 4.1 System diagram for three phase APF-IBC

The control strategy of three phases is same as the half bridge buck converter. The modulation method is same as before that is "half cycle modulated current control". Harmonic detection method is only different. It is discussed later on. The three phase load current is sensed by current sensors and fed to *abc* to *dq0/pq0* transformation block. Then it is used to generate the reference current then it is again converted to *abc* frame and fed to logic and drive circuit. Logic and drive circuit generates the pulses for three phase APF-IBC based upon the error between reference compensating current and actual compensating current.

4.2.2 Interleaved structure of three phase APF

Fig. 4.2 Shows interleaved structure of a three phase APF-IBC. It is parallel combination of three half bridge interleaved buck converter across a dc-link capacitor. For negative current and higher frequency S_1, S_3, S_5 operates and for positive compensating current and higher frequency S_2, S_4, S_6 operates. In low frequency range during positive current D_2, D_4, D_6 and during negative current D_1, D_3, D_5 conducts current.

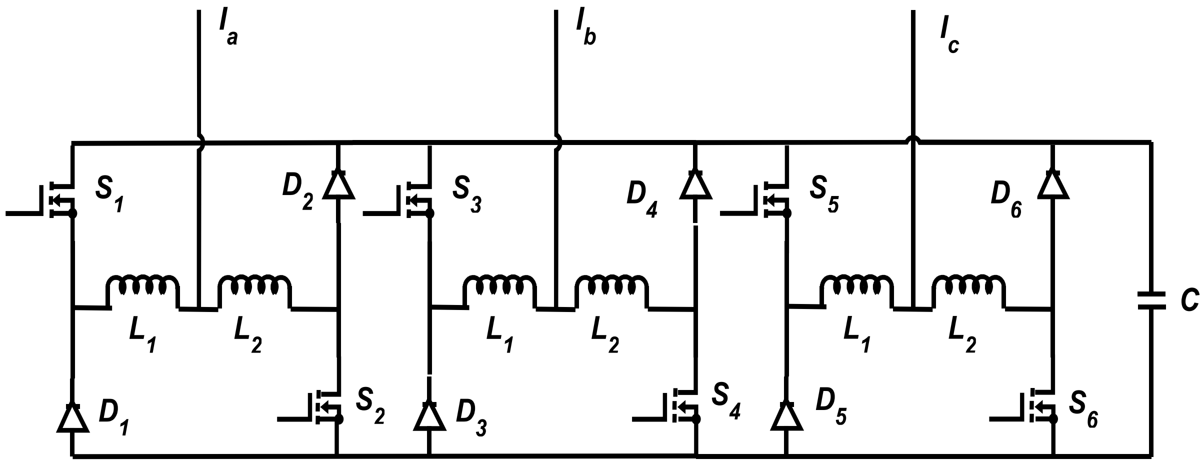


Fig. 4.2 Interleaved structure of three phase APF-IBC

4.2.3 Harmonic detection block

By the inverse Park transformation the first harmonic load current of positive sequence transformed to dc quantities. These represent the harmonic current system that must be preserved in the mains. The ac components of the load current must be injected by the AF. These ac quantities are which derived from the load currents through the APF presented in Fig. 4.1. Low-pass Butterworth fourth-order switched capacitor filters are used. The cutoff frequency chosen is simply the fundamental frequency. This assures a small phase shift in harmonics and a sufficiently fast transient response in the APF harmonic compensation. The fourth-order filter gives the best performance.

A proportional integral (PI) controller voltage regulation used on the VSC dc side. Its input is the capacitor voltage error. Through regulation of the first harmonic direct current of positive sequence it is possible to control the active power flow in the VSC and thus the capacitor voltage. The reactive power flow may be controlled by the first harmonic quadrature current of positive sequence.

As described above, the direct voltage component is always equal to the amplitude of the voltage space vector. Under balanced sinusoidal voltage conditions $u_d=\sqrt{3}U$, where U is the mains RMS voltage. Assuming that the active power flow between mains and the VSC is equal to the active power on the dc side, i.e., ignoring the losses in the inductance and switching devices, then p= $u_d i_d = u_{dc} i_{dc}$, where i_{dc} is the variable is the current in the capacitor.

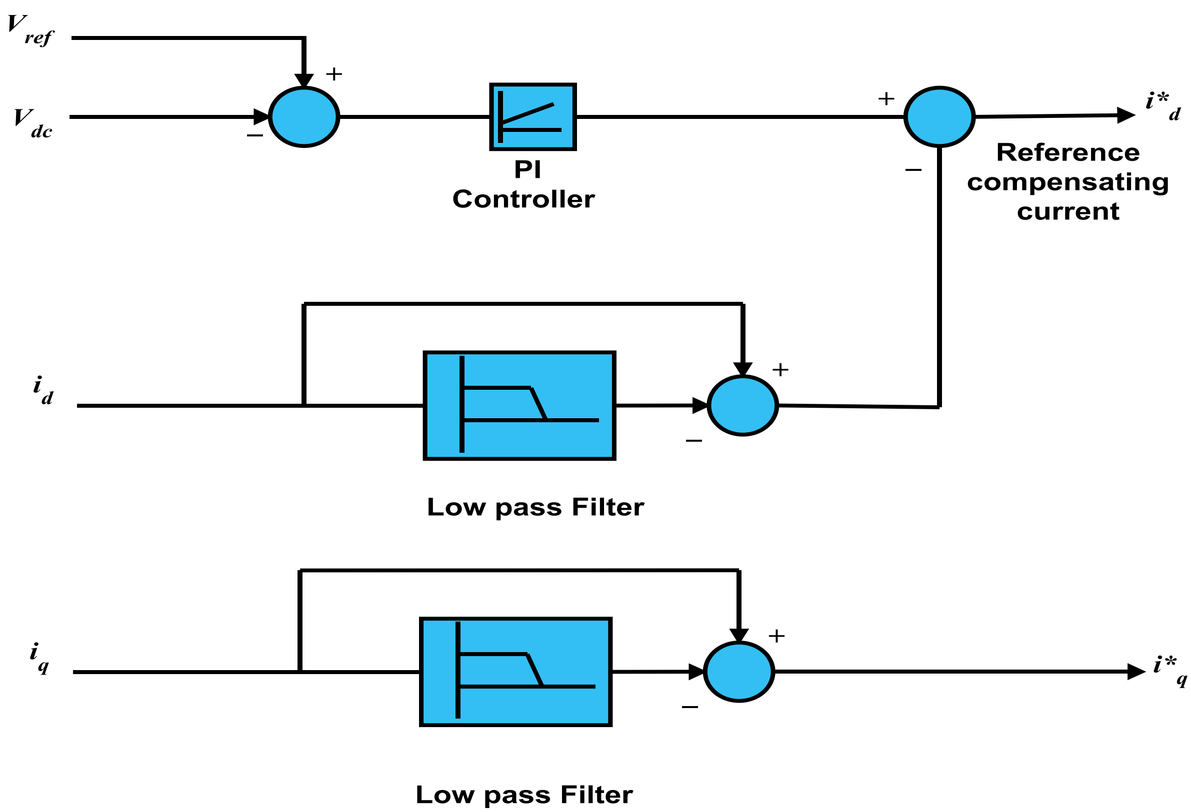


Fig. 4.3 Reference compensating current generation circuit

4.2.4 Current control strategy

The current control for three phase system is same as the half bridge system only the reference current is different. According to that the control signals also differs from the half bridge topology. In this case also during positive current different switches and during negative current different switches operates irrespective of the positive or negative half cycle. This leads to elimination of shoot through and increase in reliability of the three phase active power filter.

The high frequency control signal is obtained by modulation of the output of current controller and carrier wave. The low frequency control signal is obtained from zero crossing detection of the reference compensation signal. Fig. 4.4 illustrates the above methodology of current control. Here also we can see that per phase during positive current one switch and during negative current another switch operates irrespective of the positive and negative half cycle. So the total modulation is dependent on the reference compensating current and the error of actual and reference current.

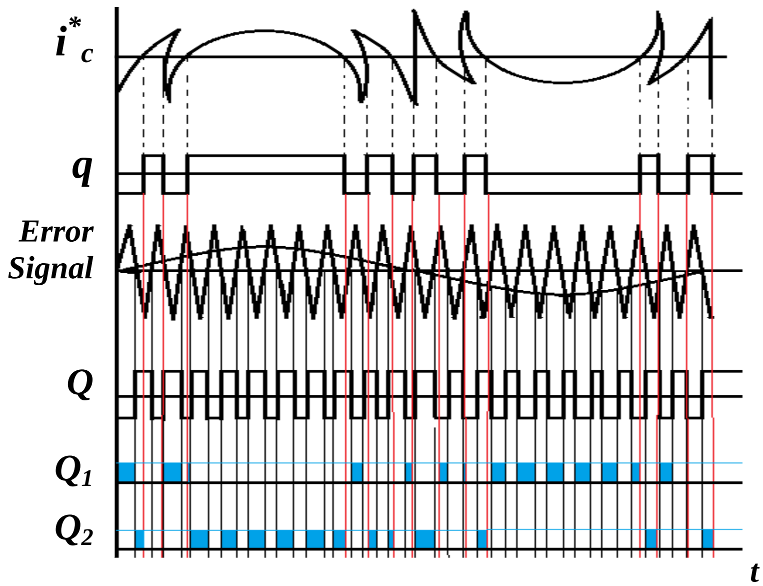


Fig. 4.4 Modulation methodology of three phase APF-IBC

4.3 Three phase four wire APF based on IBC

4.3.1 System description

Fig. 4.5 gives the system diagram of three phase four wire system. The structure of a shunt active power filter used for three-phase four-wire is shown in Fig. 11. In this system, the load produce harmonics and unbalance current in three-phase and current is flown in neutral wire. The total system is same as the three phase system only another extra block that is zero sequence current calculation.

Three-phase four-wire system is different from three-phase three-wire system because of the neutral wire. In this case handling zero-sequence components of three-phase current is the key point. Reference current calculating circuit should product the reference current correctly and fast in three-phase four-wire system. That means it should detect the harmonics, negative-sequence fundamental current components and zero-sequence current components of the compensating.

The generation circuit of compensating current should product compensating current correctly according to the reference current signals. Because the sum of three-phase current is not zero in three-phase four-wire system the detection method based on instantaneous reactive power theory should be modified. The way is to calculate the zero-sequence current components then subtract them from three-phase current. Finally three-phase current without zero-sequence components can be detected by the method based on instantaneous reactive power theory.

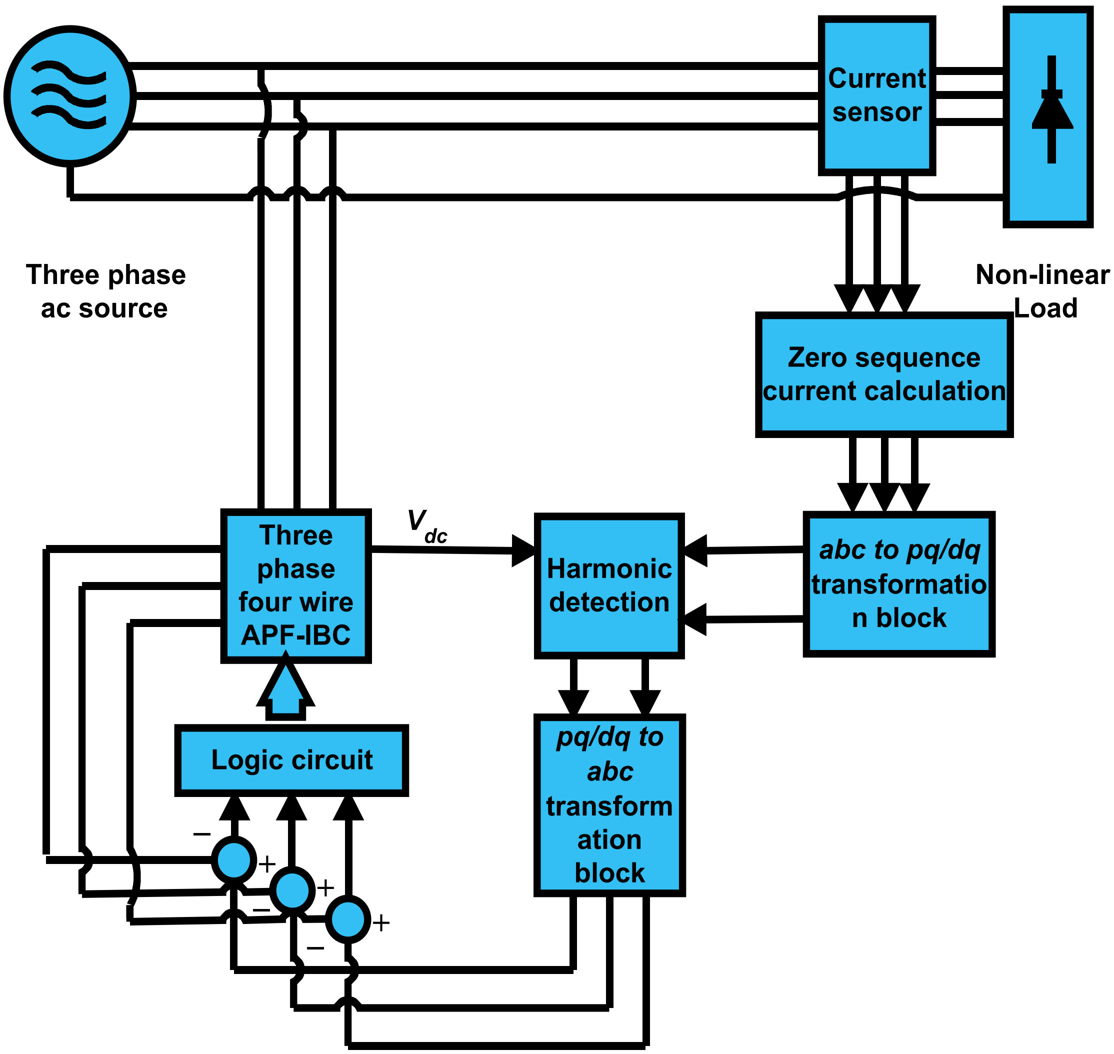


Fig. 4.5 System diagram of three phase four wire APF-IBC

The compensating current signals of the neutral wire can be also calculated by turning the polarity of the neutral wire current over. The principle of reference current calculating circuit is shown in Fig. 10. The zero-sequence component of three-phase current is calculated as:

$$i_n = \frac{1}{3}\left(i_a + i_b + i_c\right) \tag{5.1}$$

The zero sequence components can be subtracted from the three phase currents as follow

$$
\begin{aligned}
i_a' &= i_a - i_n \\
i_b' &= i_b - i_n \\
i_c' &= i_c - i_n
\end{aligned}
\tag{5.2}
$$

Now this current are balanced we can write as

$$
i_a' + i_b' + i_c' = 0 \tag{5.3}
$$

Other than this calculation harmonic detection current control strategy all this things are same as the three phase system. Because of extensive use for three-phase four-wire in power system such as, business, official and industry; many people pay more attention to the trouble which is caused by harmonics and unbalance of three-phase. Therefore, it is important to compensate harmonics and reactive power in three-phase four-wire system.

4.3.2 Interleaved structure of three phase four wire APF-IBC

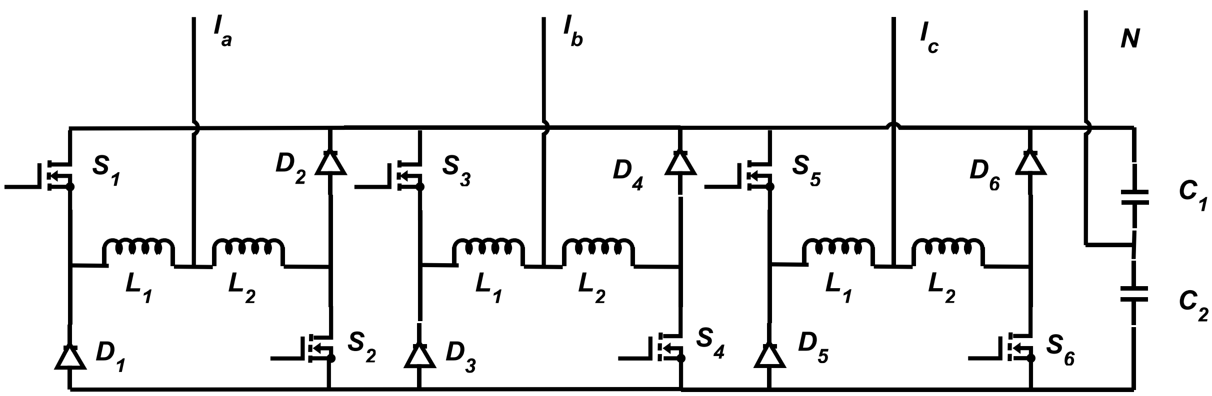


Fig. 4.6 Interleaved structure of three phase four wire APF-IBC

Fig. 4.6 shows the interleave structure of three phase four wire APF-IBC. This is similar to three phase structure only different in the form of neutral wire. The neutral wire can be connected with another half bridge configuration in parallel with the existing three but it will cost more and the current control strategy we have to change for it. So the neutral wire is connected through dc-link split capacitor.

4.4 Chapter summary

This chapter is based on the three-phase APF-IBC and three-phase four wire APF-IBC. At first the harmonic detection technique in three phase system is discussed. And it has been found that out of two method i.e. i_d-i_q and p-q, i_d-i_q method leads to better compensating performance due to its frequency independent characteristic. A close look to three-phase interleaved structure is given along with the three-phase four wire configuration. Total filtering concept in three-phase and three-phase four wire system described with the help of block diagrams. Function of each block is described. Detail of harmonic detection and voltage control method in both three-phase and three-phase four wire APF-IBC is given.

CHAPTER- 5

5 SIMULATIONS AND RESULTS

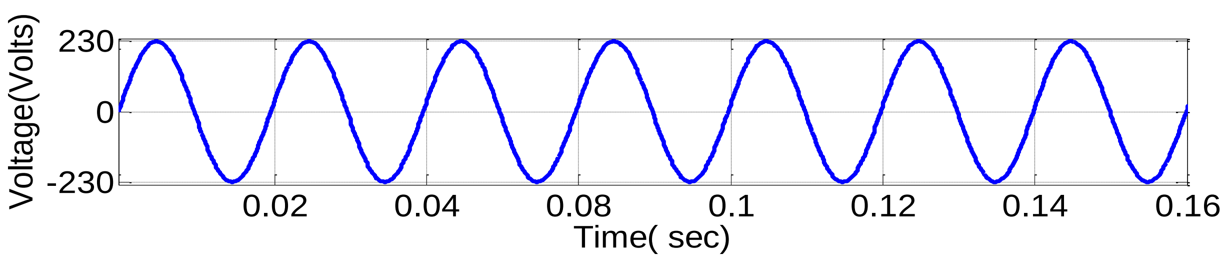
5.1 System parameter

In order to verify the feasibility of novel APF and validity of the control strategy, simulations using the "SIMULINK" software package of the "MATLAB" are taken. The prototype system power capacity is set as 2 kVA. Detailed parameters are given in Tab. I.

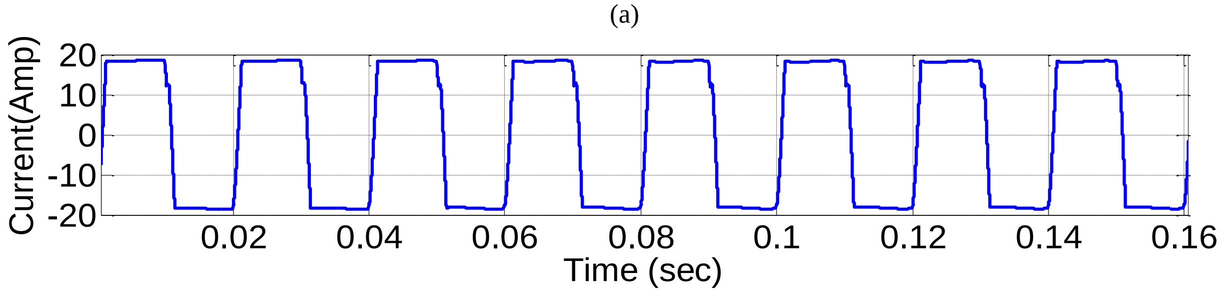
Table. I Detail simulation parameter

Parameter	Value
Phase voltage U_S /V	230
Lines frequency f_S /Hz	50
Power capacity S /kVA	2
Boost inductor L /µH	600
DC-link capacitor C /µF	1000
DC-link voltage U_{dc} /V	400

5.2Simulation results without APF

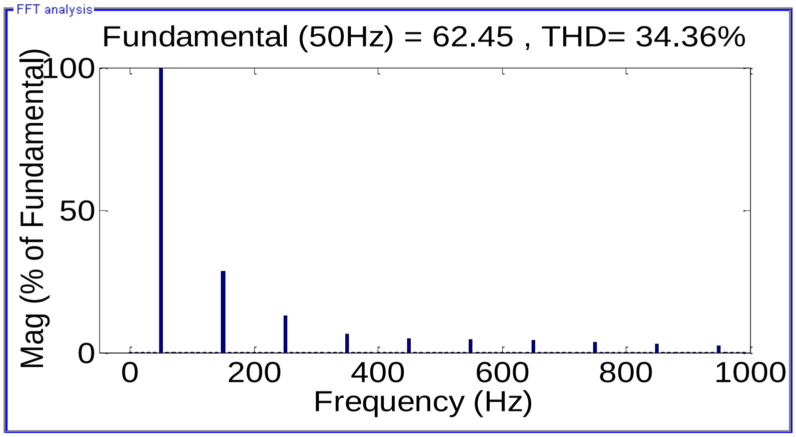


(a)



(b)

Without active power filter the source current is equal to the load current and the THD value is high i.e. 34.36% here. It can be more also and depends upon the load value. Fig. 5.1 shows all the corresponding waveforms.

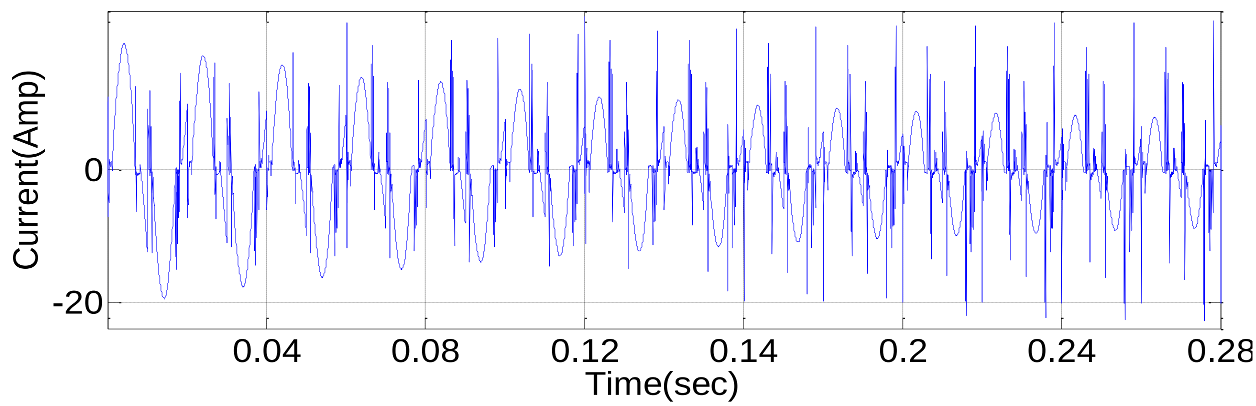


(c)

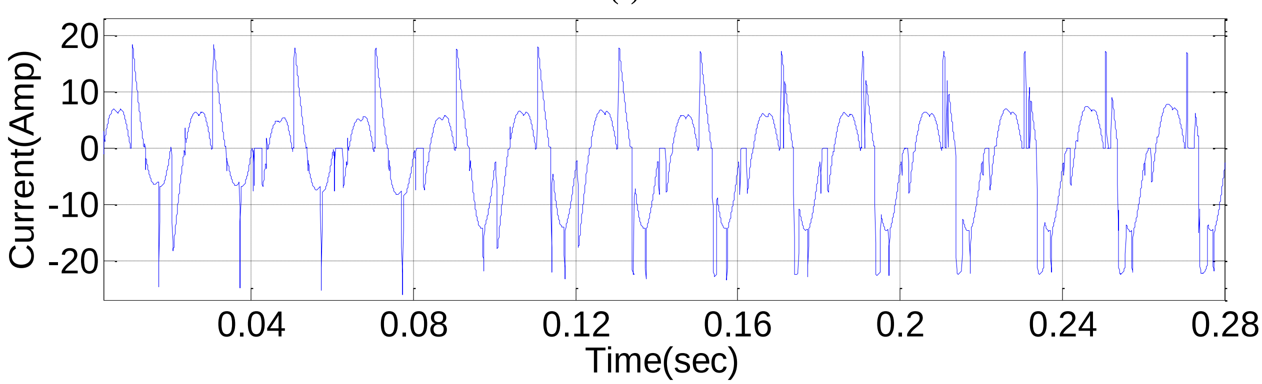
Fig. 5.1(a) Source voltage with no compensation, (b) source current with no compensation, (c) THD without compensation

5.2 Simulation results with APF

5.2.1 Shoot through in normal converter



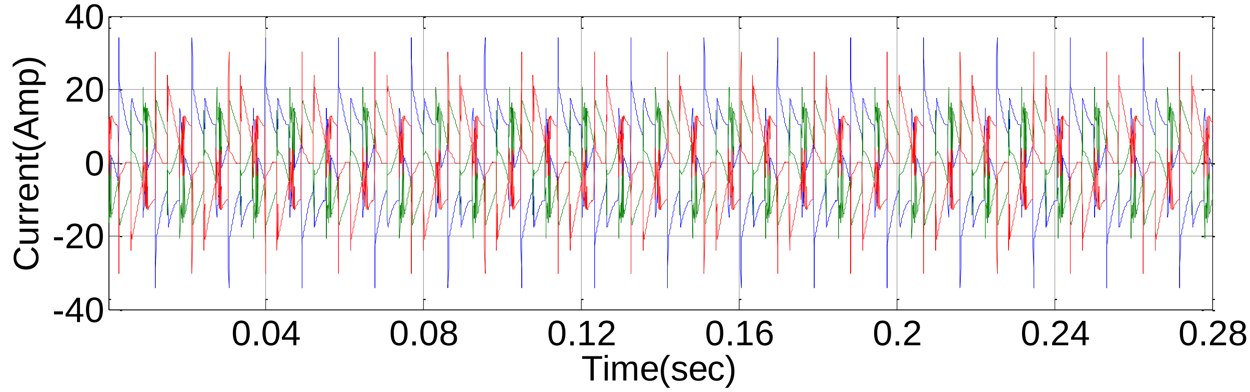
(a)



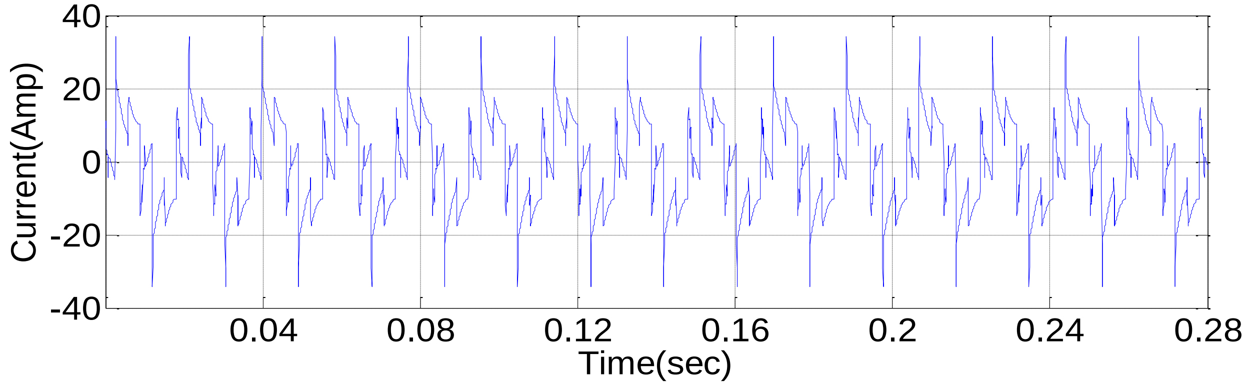
(b)

Fig. 5.2 (a) (b) Compensating current showing shoot through phenomena in single phase

We can see from Fig.5.2 (a), (b) due to shoot through phenomena current suddenly raises to a value twice or thrice of original value. These results are obtained from a normal voltage source converter. Gradually the compensation performance also deteriorates. Fig. 5.3 (a), (b) shows shoot through phenomena in three phase system. 5.3 (a) shows three phase view and 5.3 (b) shows single phase view to observe more clearly.

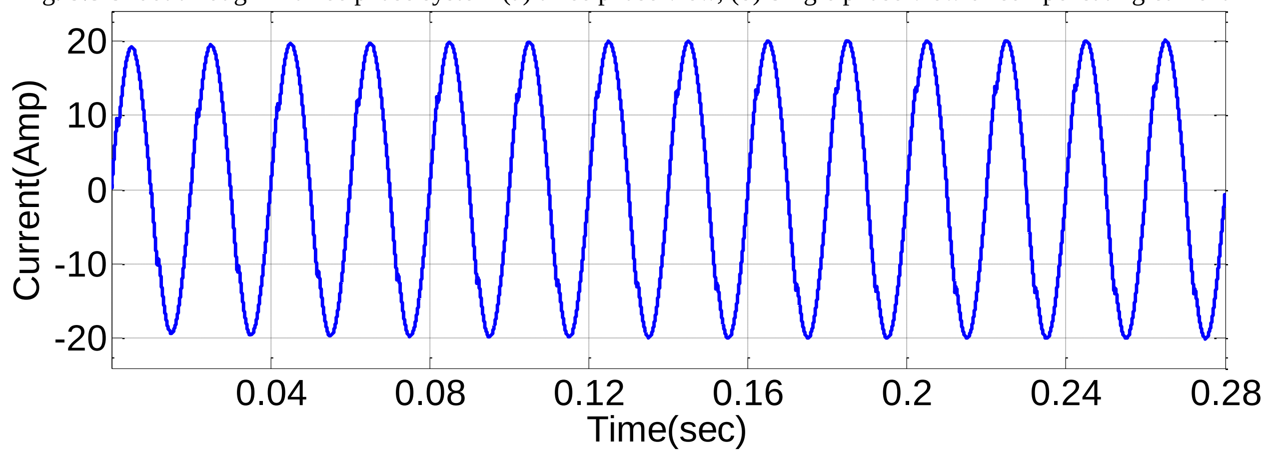


(a)

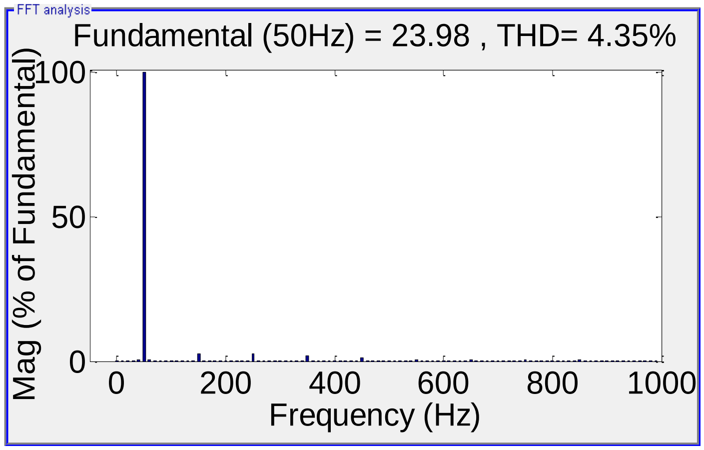


(b)

Fig. 5.3 Shoot through in three phase system (a) three phase view, (b) Single phase view of compensating current



(a)



(b)

Fig. 5.4 (a) Source current, (b) THD Value of source current with shoot through phenomena in APF

5.2.2 Effect of dead time

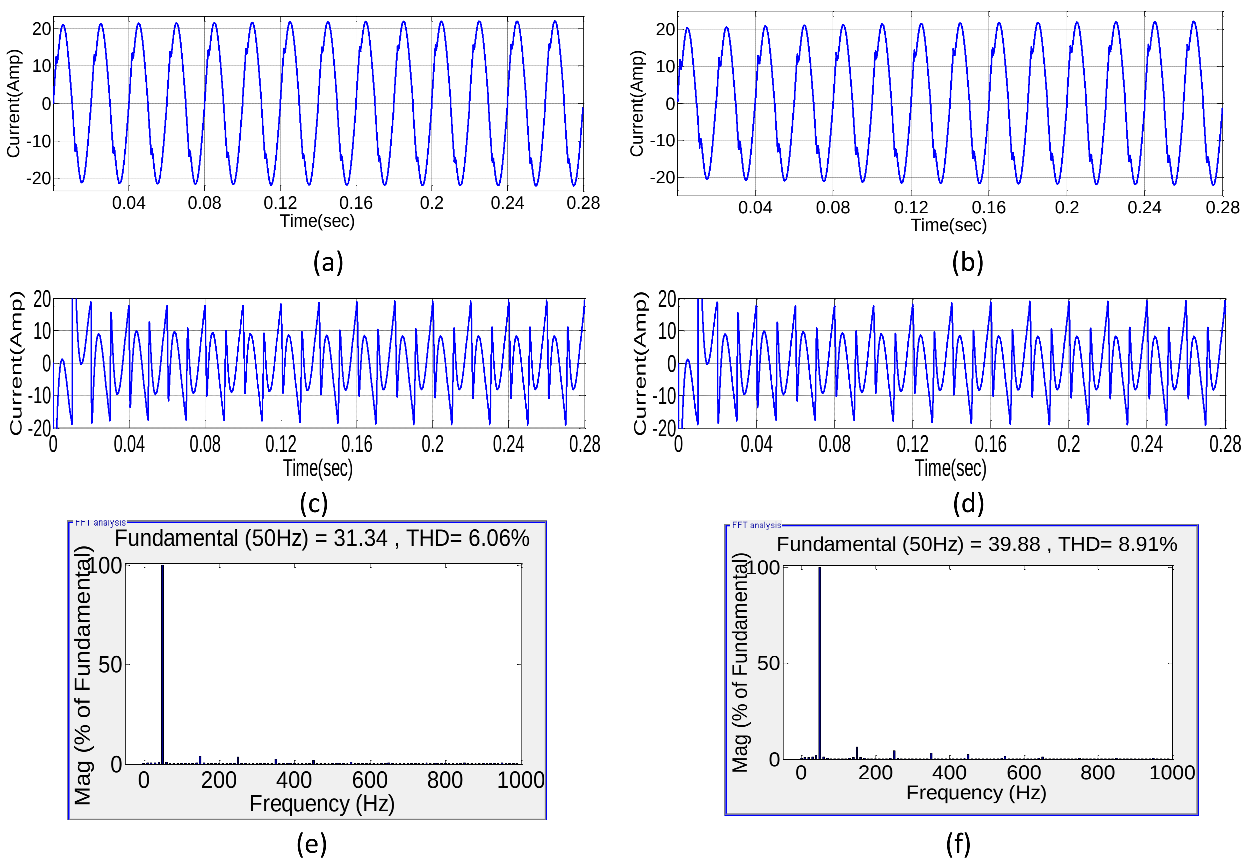
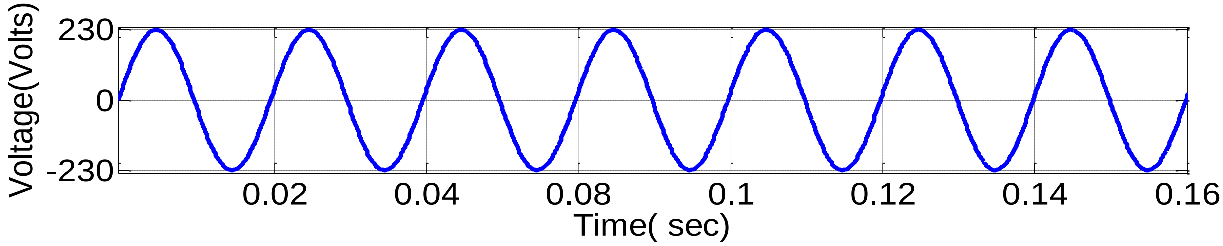


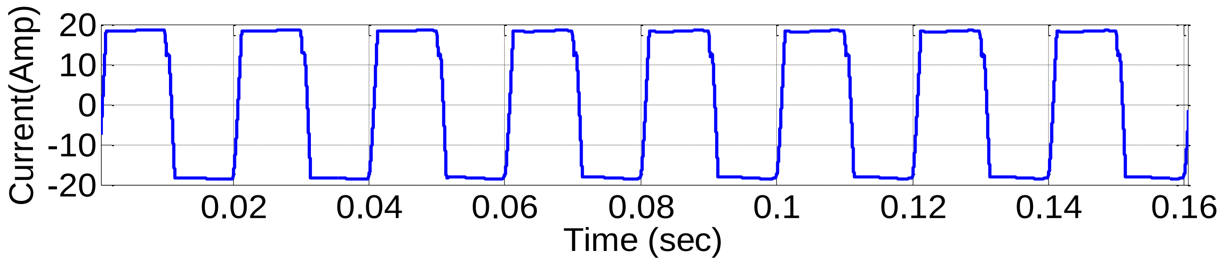
Fig. 5.5 (a) Source current, (c) THD with dead time 2 μs, (b) Source current, (d) THD with dead time 4 μs

It has been observed that with dead time the shoot through phenomena is eliminated but with increase in the dead time value compensation performance is decreasing and the THD value increases

5.2.3 Half bridge topology



(a)



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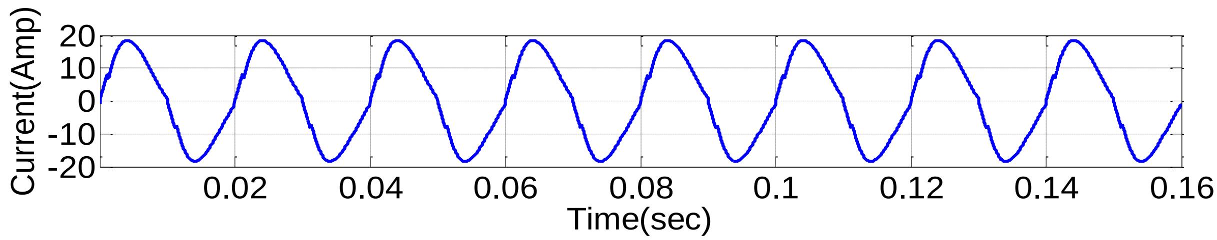

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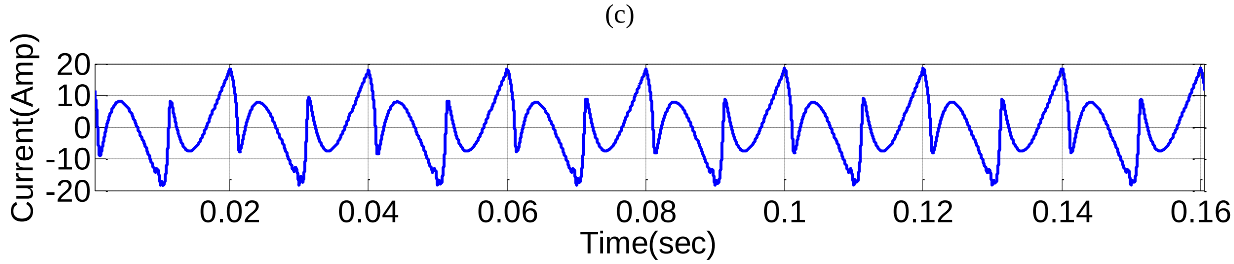

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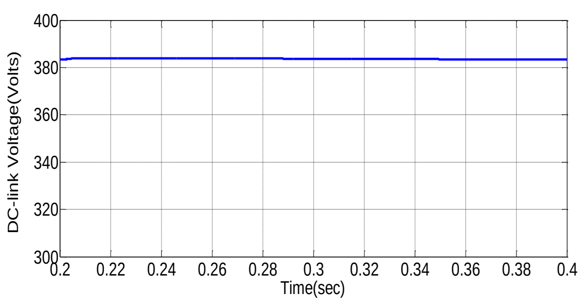

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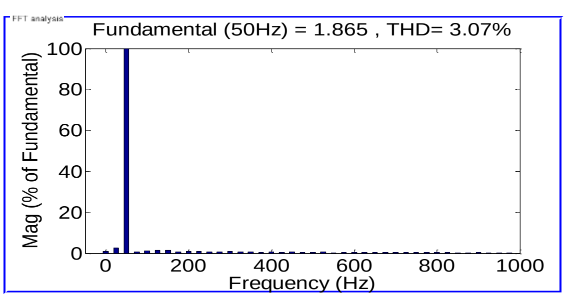
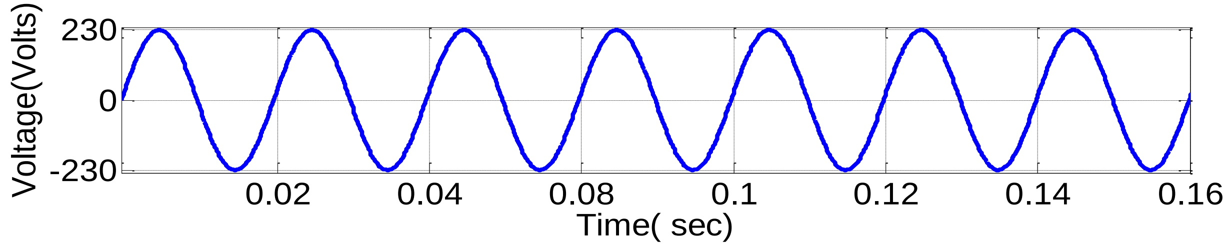


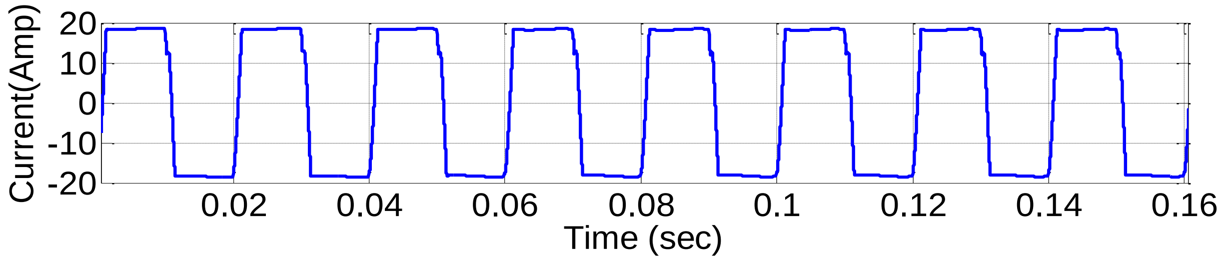
(f)

Fig. 5.6 (a) source voltage, (b) Load current, (c) Source current, (d) compensating current, (e) dc-link voltage, (f) THD value of source current for half bridge topology

5.2.4 Full bridge topology



(a)



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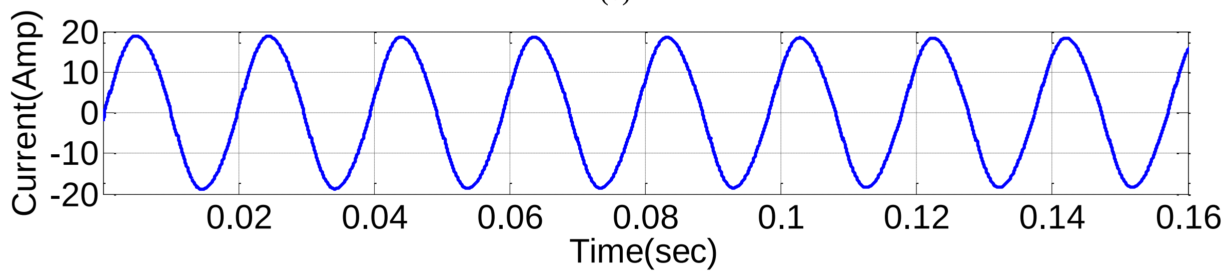

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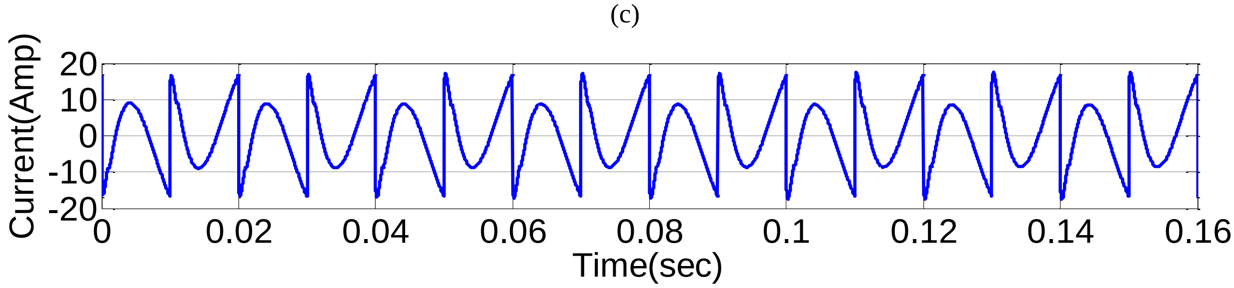

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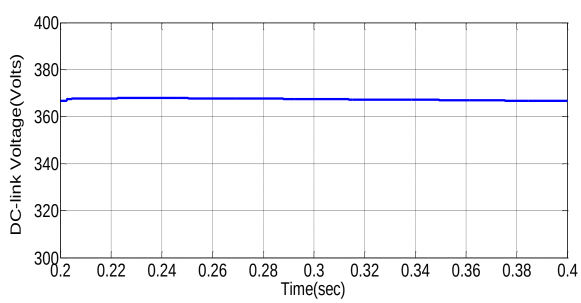
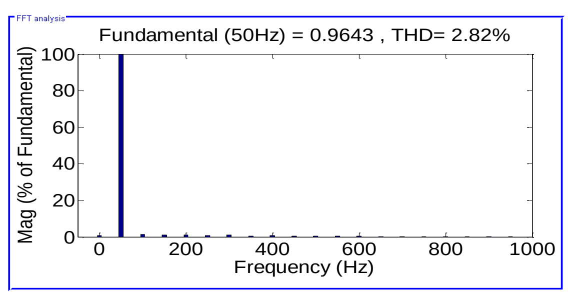


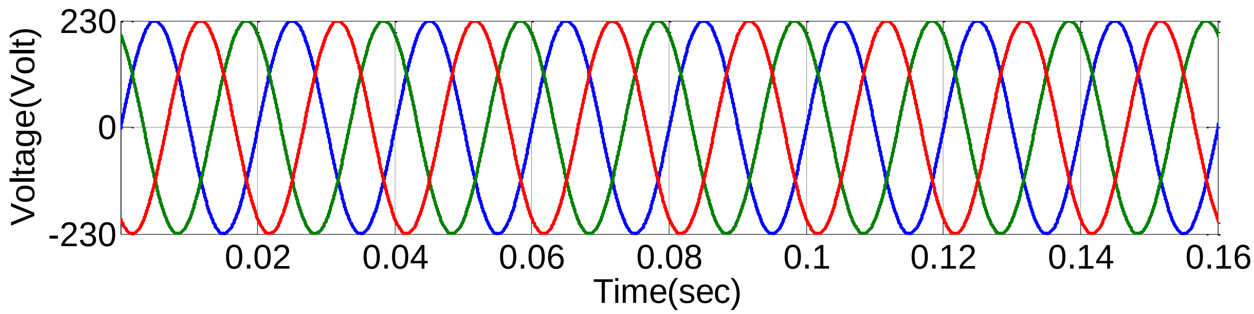


(e) (f)

Fig. 5.7 (a) source voltage, (b) Load current, (c) Source current, (d) compensating current, (e) dc-link voltage, (f) THD value of source current for full bridge topology

5.3 Simulation result of three phase system

5.3.1 Results for *p-q* method



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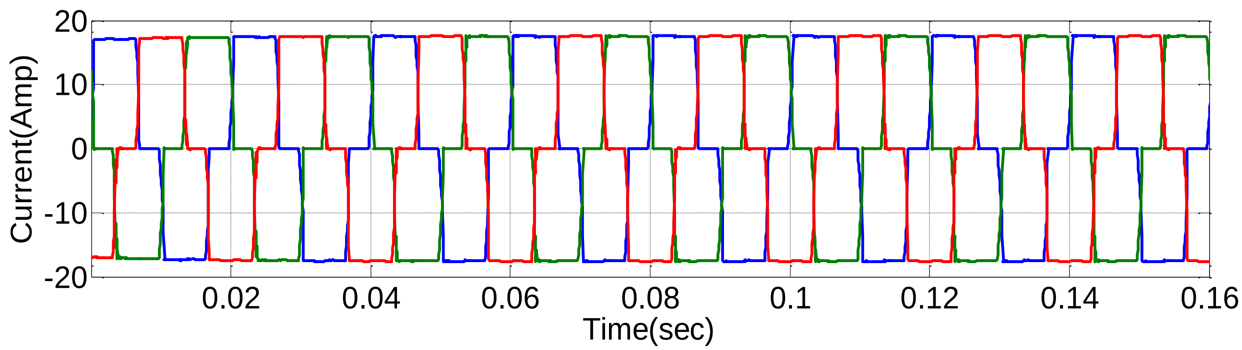

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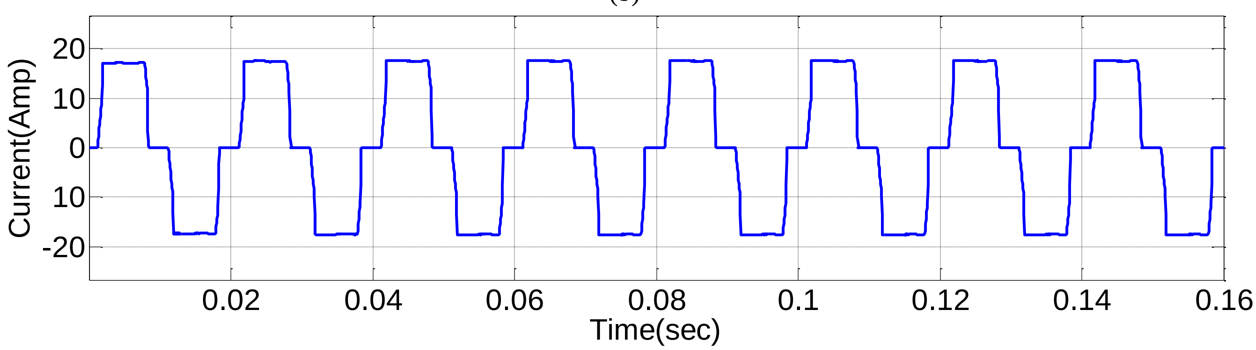

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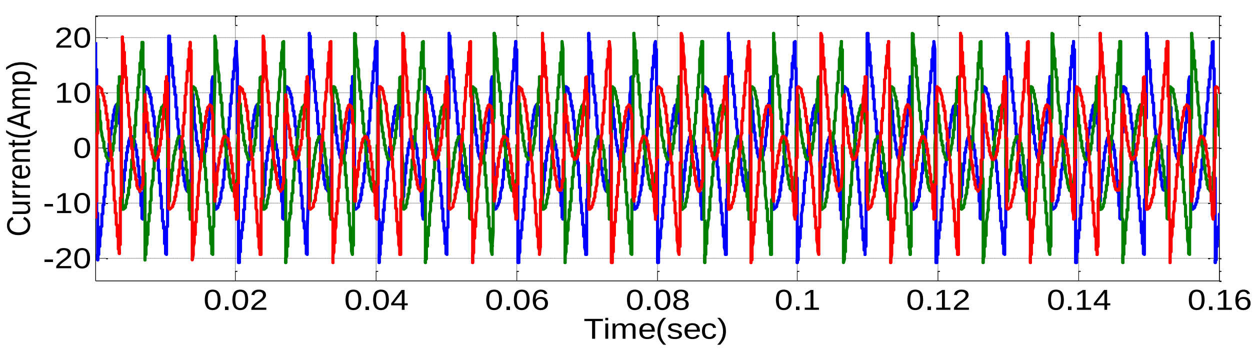

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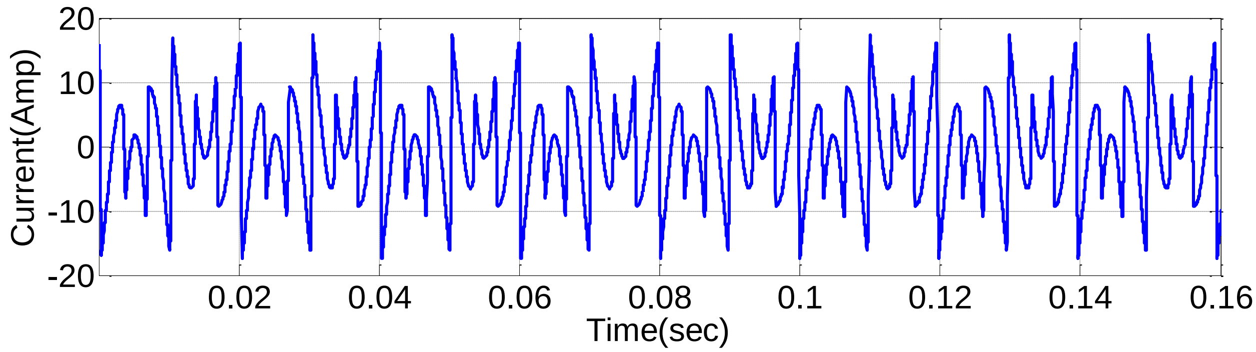

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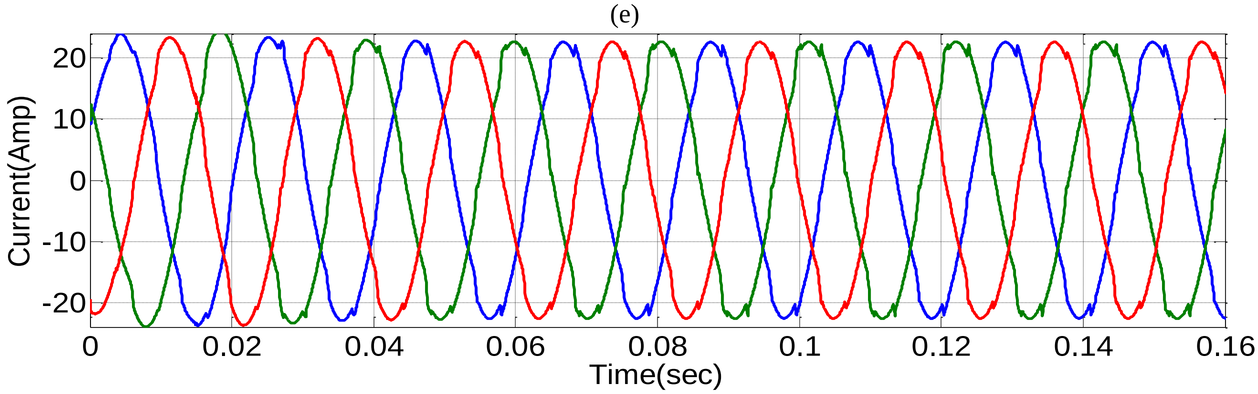

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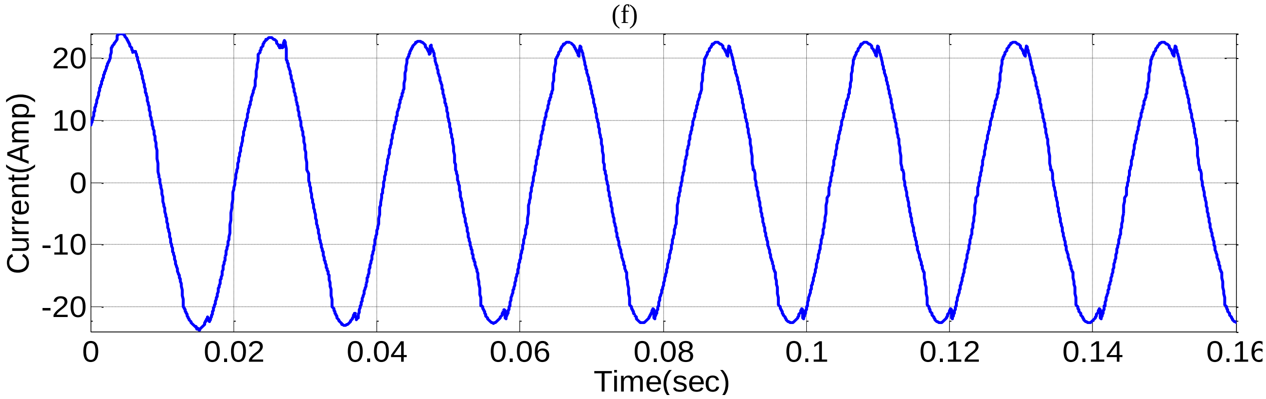

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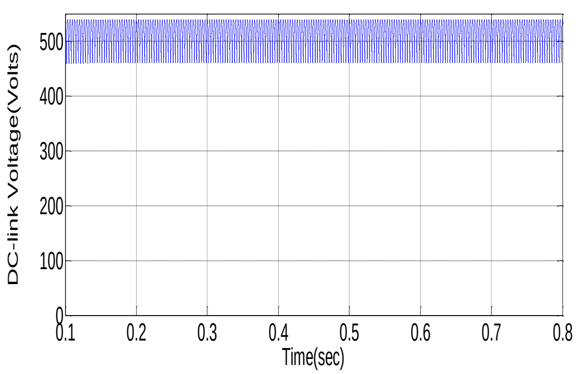

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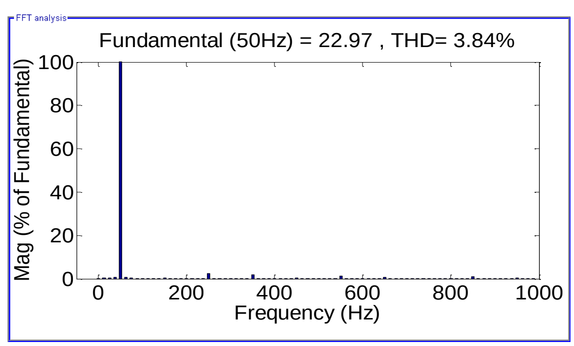
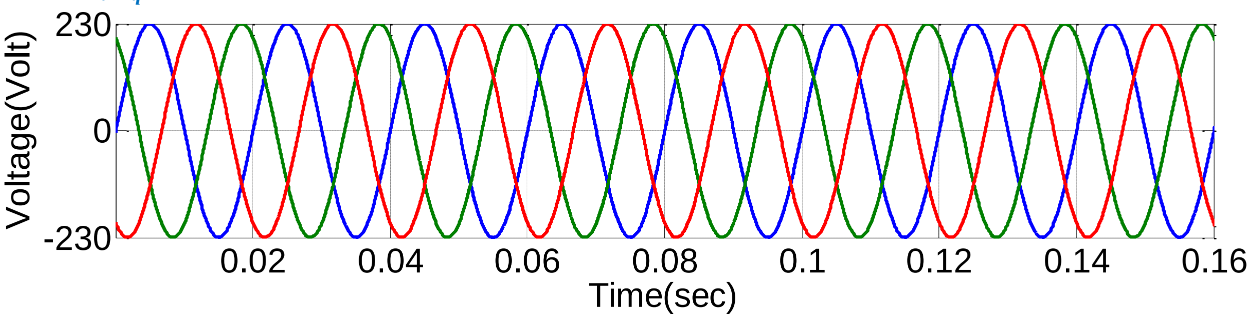


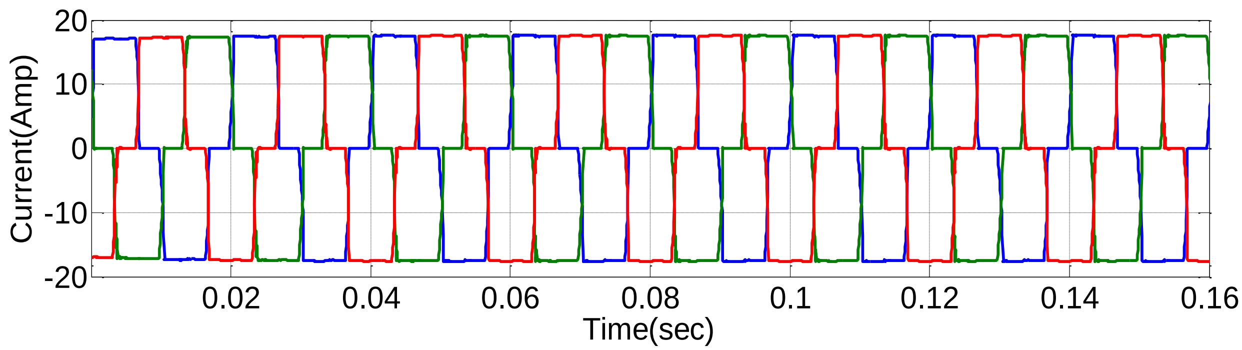
(i)

Fig. 5.8(a) source voltage, (b)(c) Load current, (d)(e) compensating current, (f)(g) Source current, (h) dc-link voltage, (i) THD value of source current in three phase APF-IBC for *p-q* method

5.3.2 i_d-i_q method



(a)



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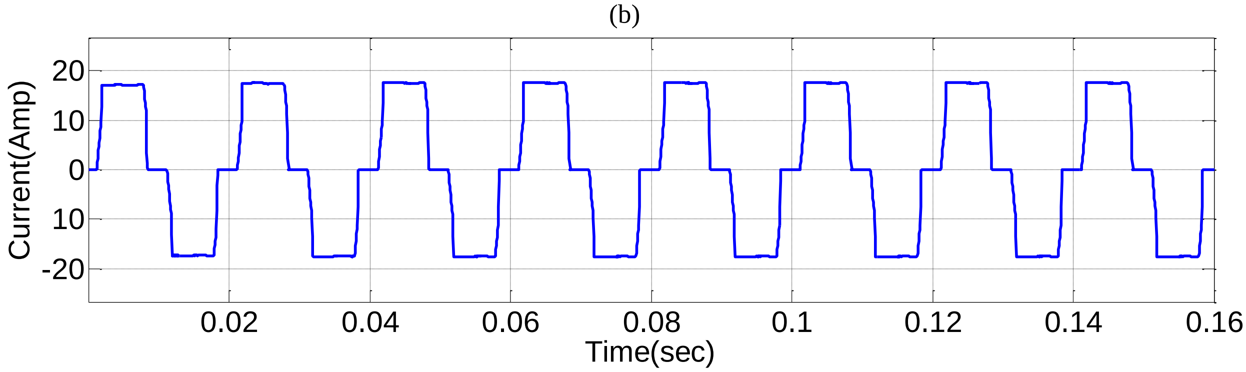

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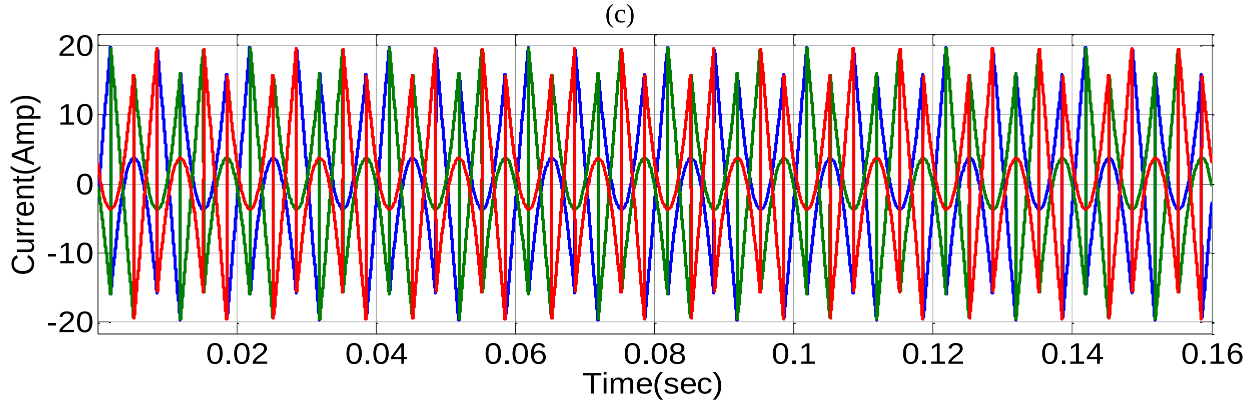

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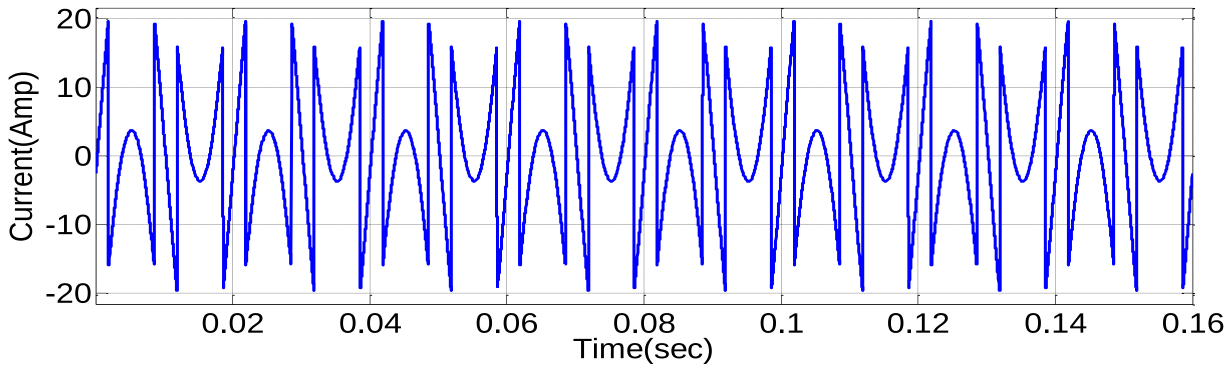

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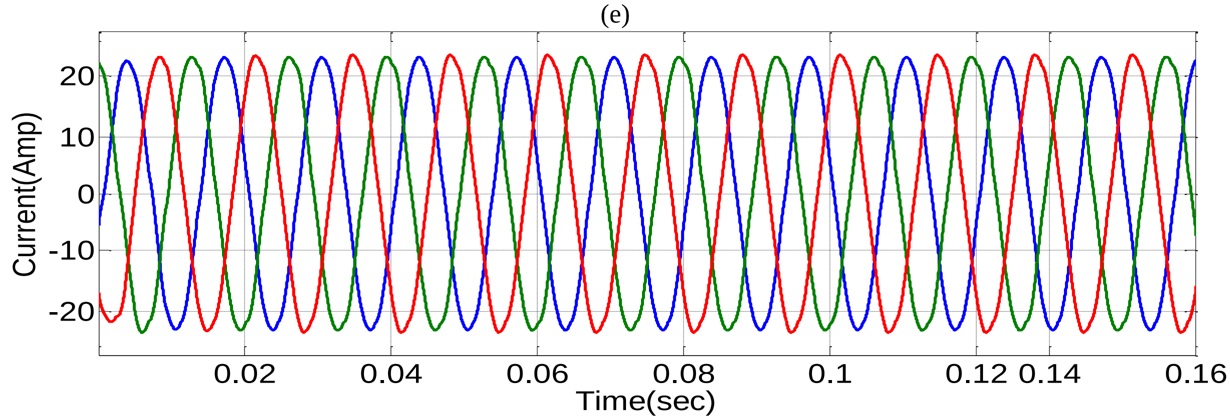

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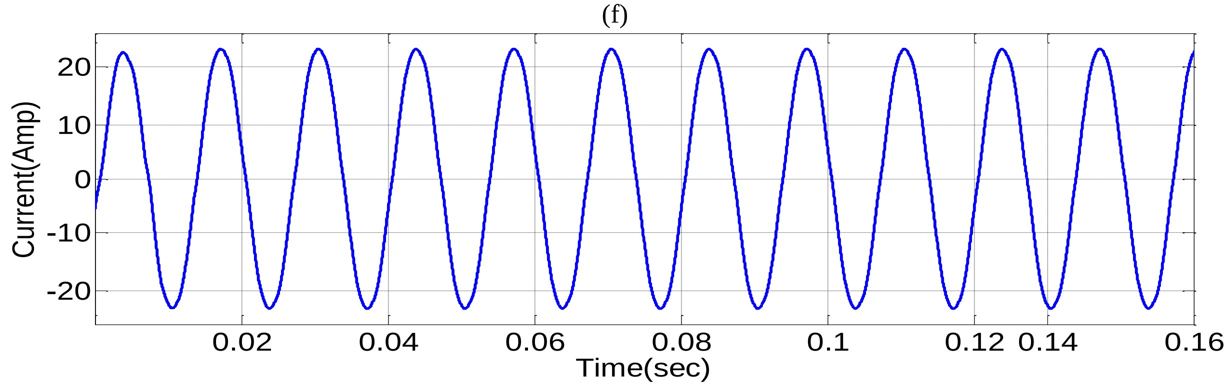

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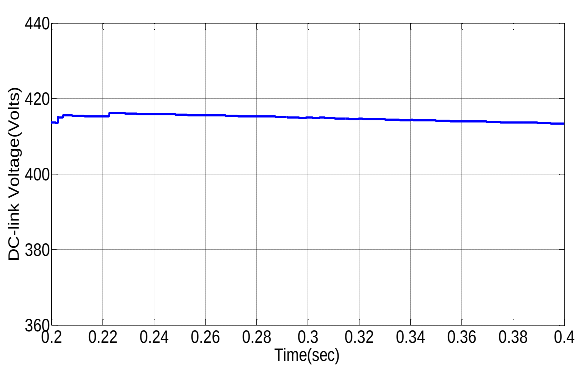

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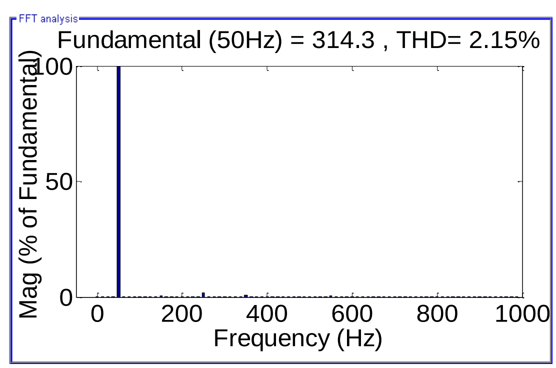
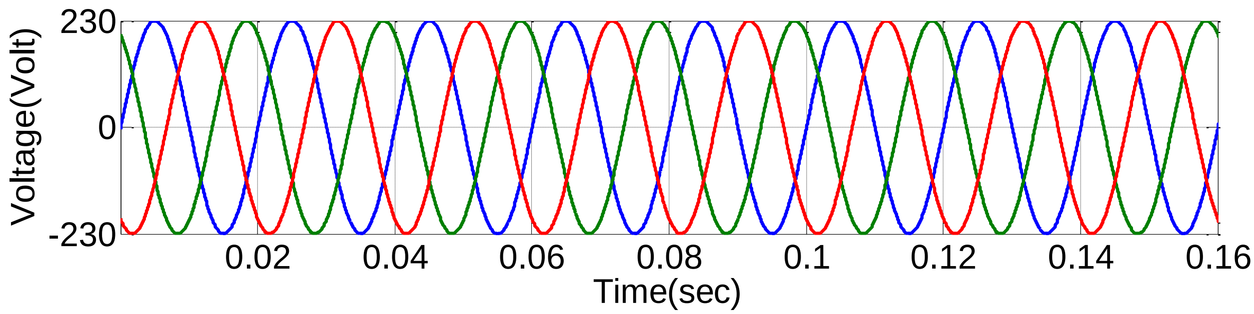


(i)

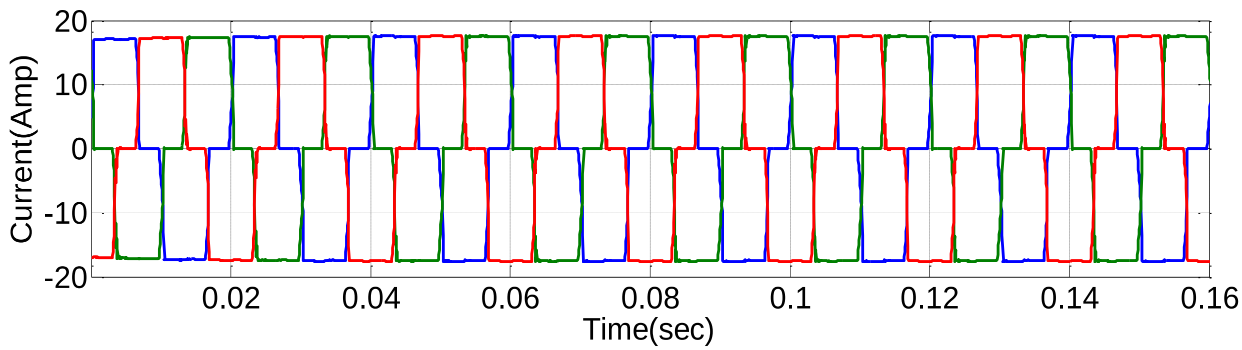
Fig. 5.9(a) source voltage, (b)(c) Load current, (d)(e) compensating current, (f)(g) Source current, (h) dc-link voltage, (i) THD value of source current in three phase APF-IBC for i_d-i_q method

5.4 Simulation results of three phase four wire system

5.4.1 p-q method



(a)



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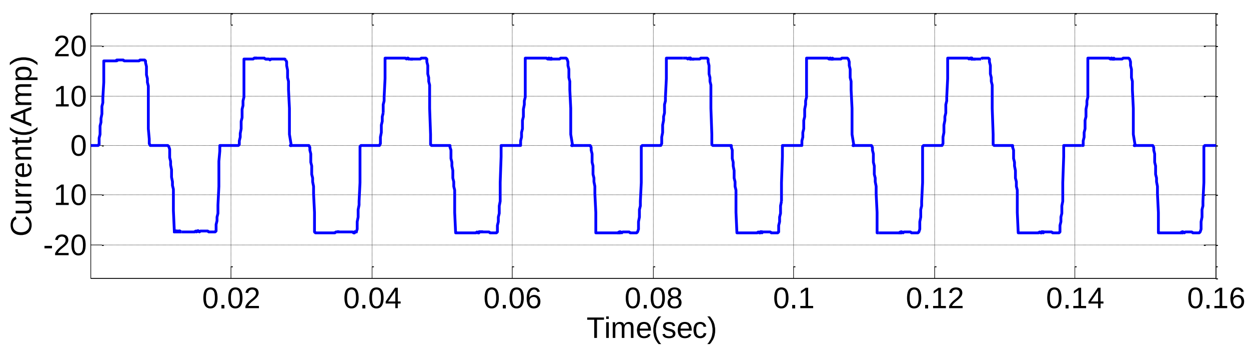

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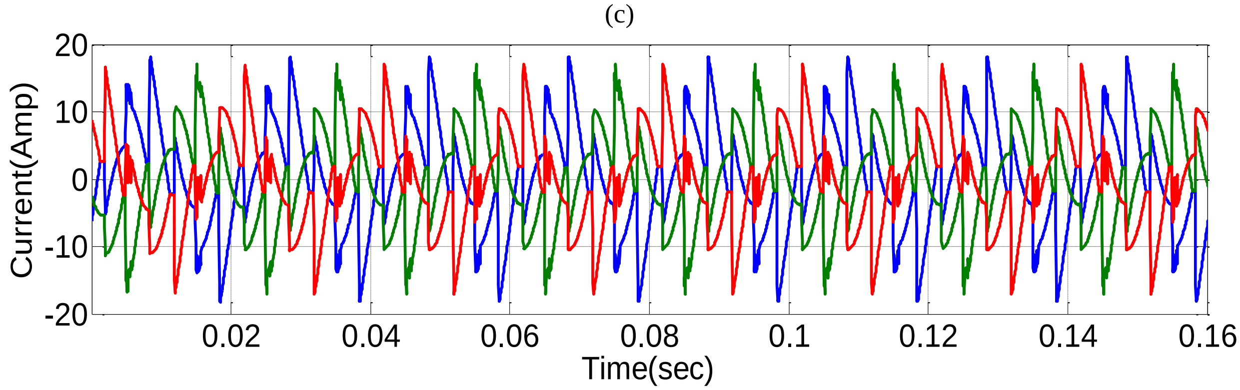

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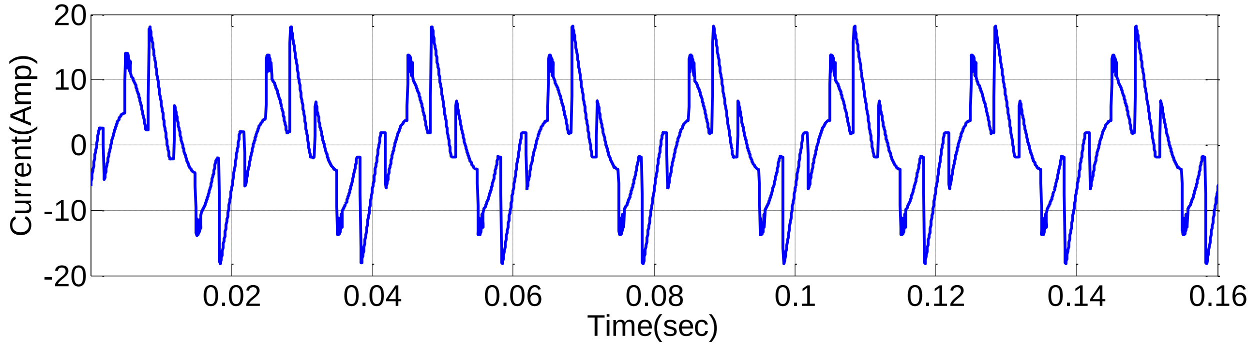

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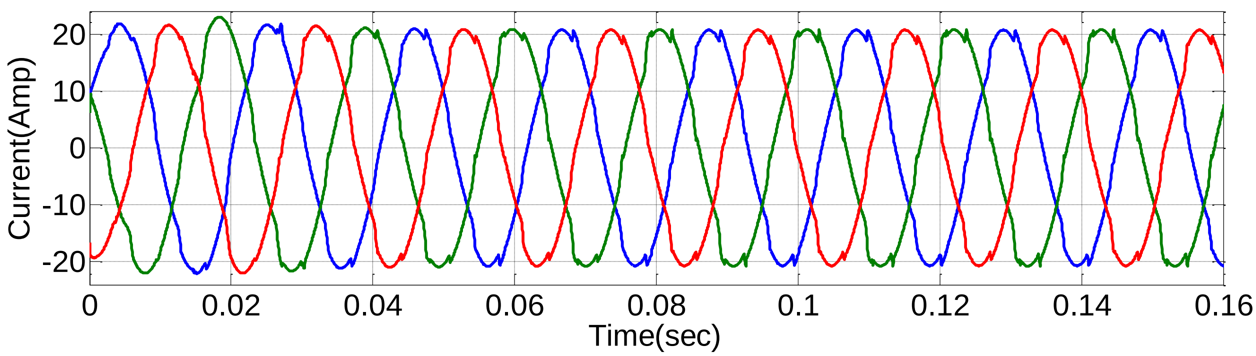

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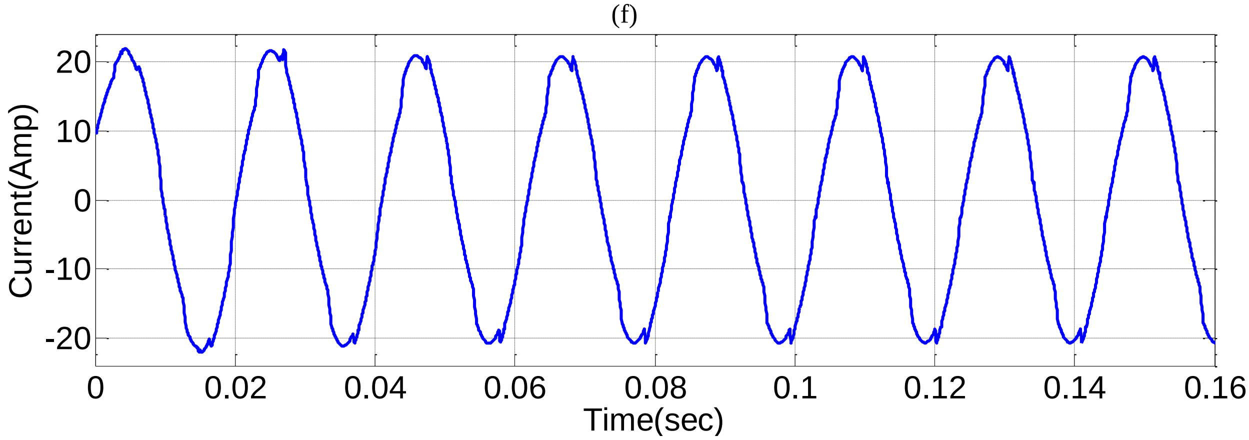

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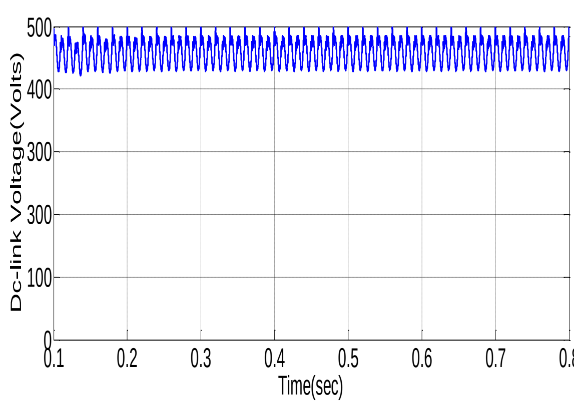
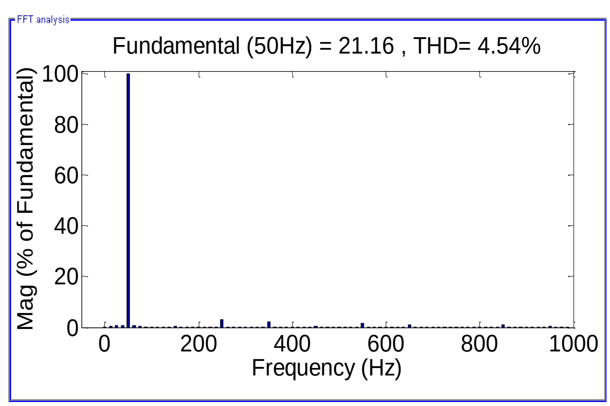
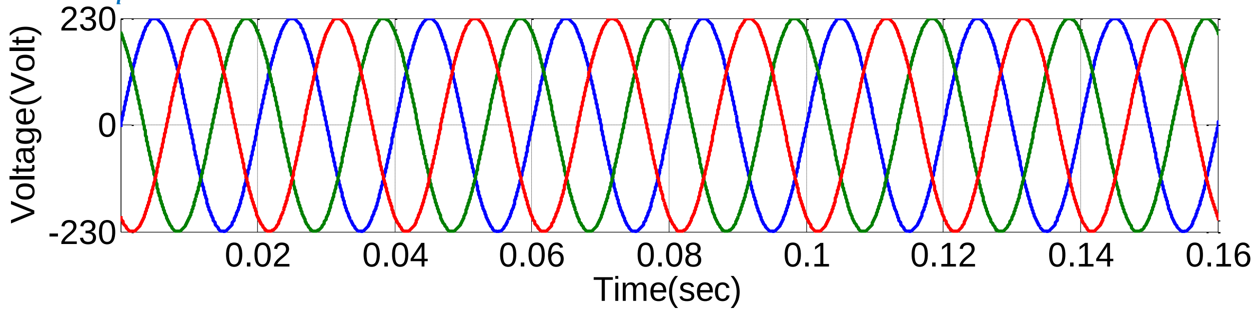




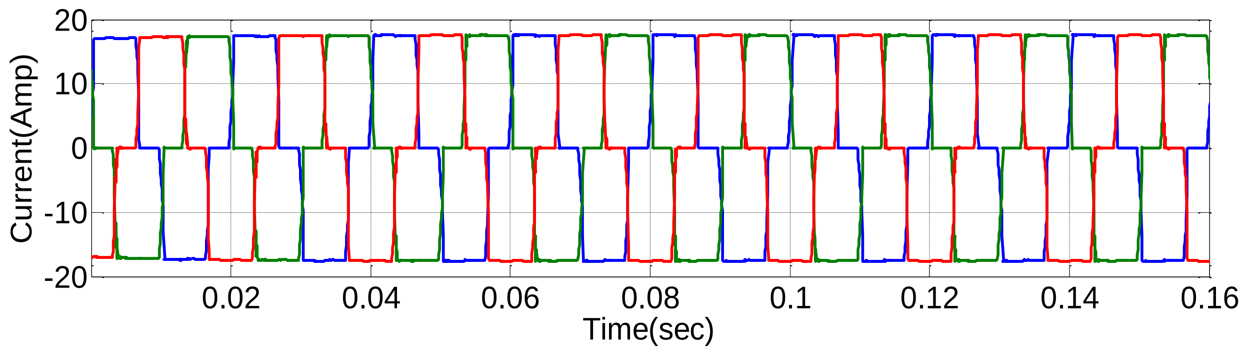
(h) (i)

Fig. 5.10(a) source voltage, (b)(c) Load current, (d)(e) compensating current, (f)(g) Source current, (h) dc-link voltage, (i) THD value of source current in three phase four wire APF-IBC for *p-q* method

5.5.2 i_d-i_q method



(a)



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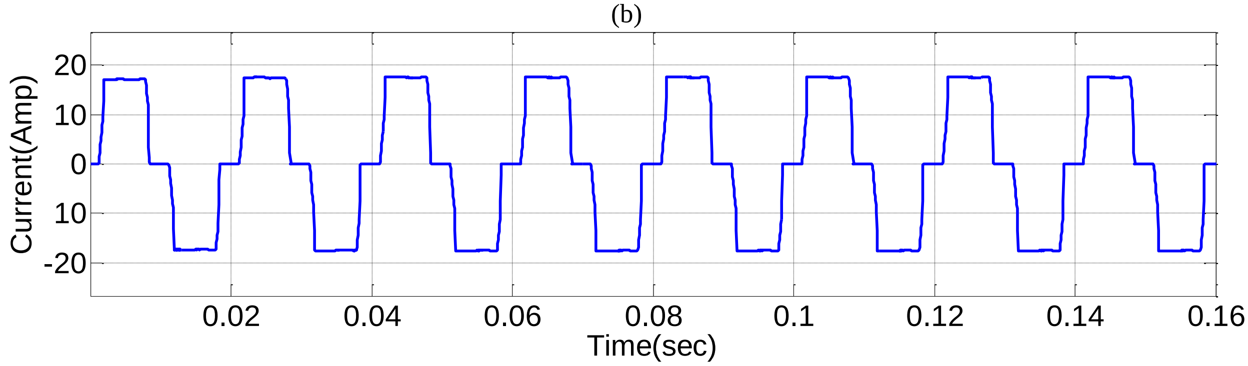

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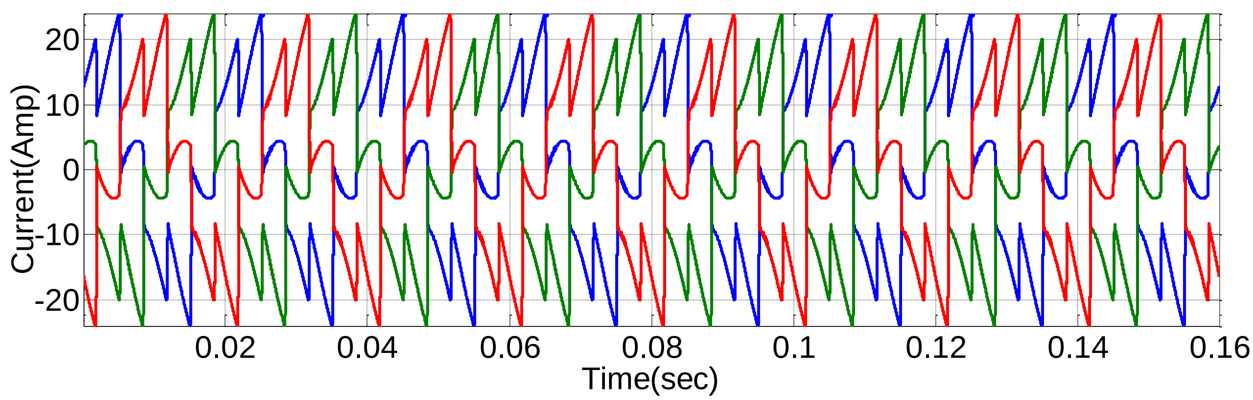

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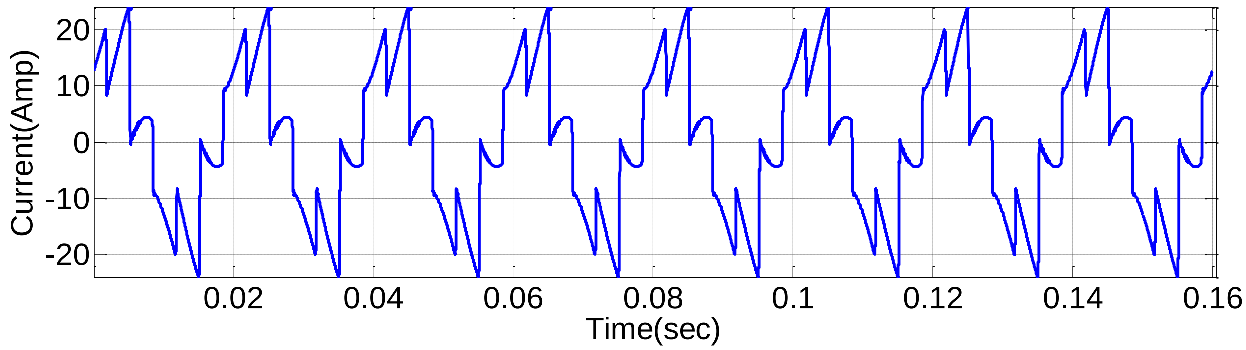

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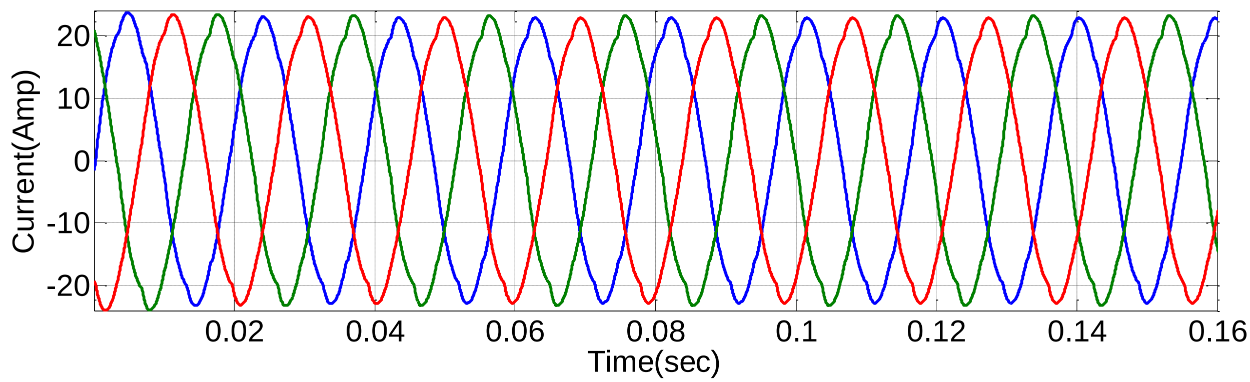

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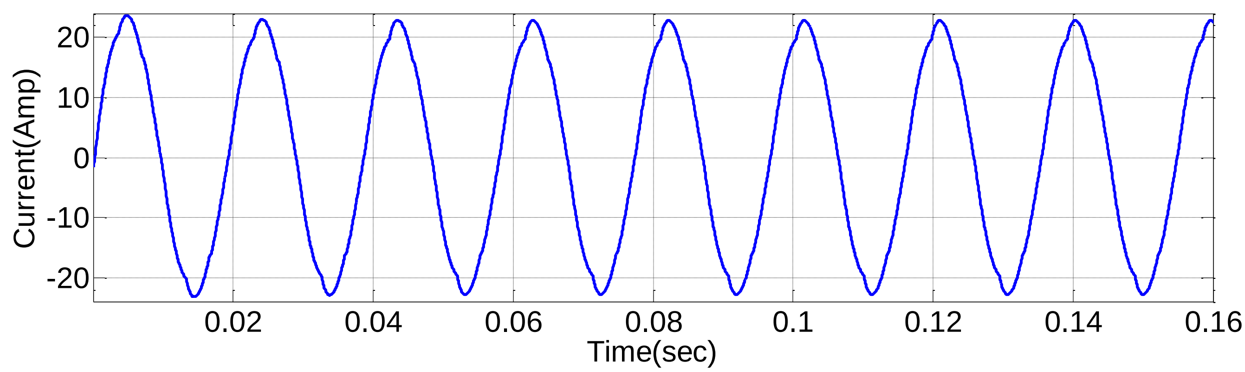

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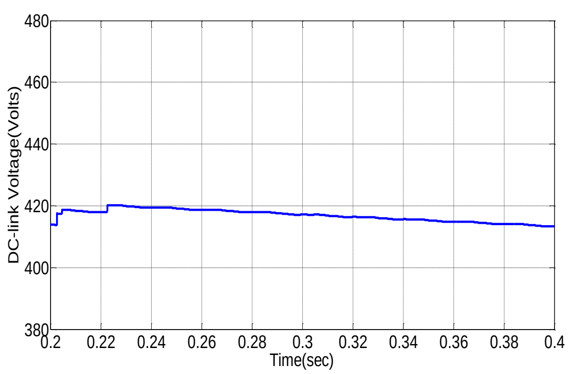
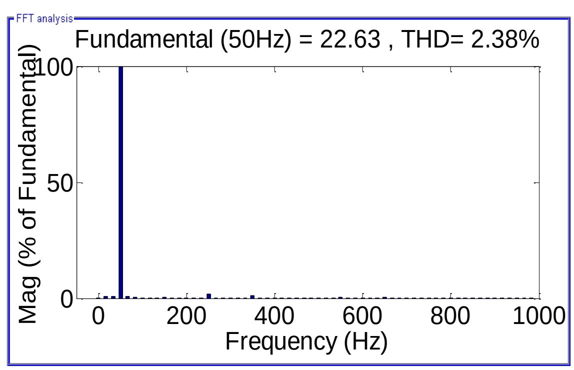


(h)



(i)

Fig. 5.11(a) source voltage, (b)(c) Load current, (d)(e) compensating current, (f)(g) Source current, (h) dc-link voltage, (i) THD value of source current in three phase four wire APF-IBC for i_d-i_q method

5.5 Comparative analysis of various topologies

We can see from the above simulation results that "shoot through phenomenon" can be eliminated in two ways: first introducing dead time in firing pulse and second with the help of interleaved buck configuration. But disadvantage of dead time is it will increase the THD level on increasing dead time. Fig. 5.5 gives the results which illustrates the effect of dead time.

Fig. 5.6 and Fig. 5.7 show results for half bridge and full bridge APF-IBC. Both the configuration eliminates shoot through phenomena without adding dead time to the circuit. In case of full bridge dc-link voltage utilization is more because with higher rating it utilizes same voltage as half bridge configuration. We can see from the waveforms the source current is nearly sinusoidal and THD level is also less.

This interleaved configuration then applied to three-phase and three-phase four wire configuration. Two different method p-q and i_d-i_q are applied to both three–phase and three-phase four wire APF-IBC; Fig.5.8, 5.9, 5.10, 5.11 shows the simulation results respectively.

Table II gives the comparison between THD Value of all the cases. In active power filter THD is the key measure to analyze the compensation level lower the THD level higher is the compensation characteristic.

Table. II comparison of source current THD values

Case under consideration	THD
Without compensation	37.3%
With half bridge topology	3.07%
With full bridge topology	2.82%
With three phase topology with p-q method	3.84%
With three phase topology with i_d-i_q method	2.15%
With three phase four wire topology with p-q method	4.73%
With three phase four wire topology with i_d-i_q method	2.38%

From above analysis we can see that i_d-i_q method is more effective than p-q in case of compensation characteristic. Dynamic behavior of both methods is same at balanced source voltage. In case of half bridge and full bridge configuration full bridge is more effective than half bridge as the dc voltage utilization is more.

5.6 Chapter summary

This chapter illustrates the feasibility of all the chapters explained before. “Shoot through” and dead time effect is shown by simulation results. Simulation results shows with the interleaved structure “shoot through” is eliminated without adding dead time. Half bridge and full bridge topologies of APF-IBC result in good compensating performance. After that this concept is applied to three-phase and three-phase four wire APF. Simulation results prove that interleaved structure is useful in three-phase system also. A comparative study of all the results is done.

CHAPTER- 6

6 CONCLUSION

6.1 Conclusion

6.2 Scope for future work

6.1 Conclusion

Nowadays, reliability and quality of electric power is one of the most discussed topics in power industry. Numerous types of power quality issues and power problems and each of them might have varying and diverse causes.

Harmonic pollution is one of the attention seeking problems. It leads to several losses and destroys the quality of the power. To overcome these entire problems power filter is one of the best solutions. Active power filter has so many advantages over passive filter so on today scenario active power filter used mostly to eliminate harmonics from the power system. But active power filter based on VSI suffers from “shoot through” phenomena. To eliminate this phenomena dead time s added in firing pulses but it leads to poor compensating performance of the active power filter. To avoid this interleaved structure of buck converter is introduced to active power filters in this project work.

Following work carried out in this project

- Shunt active power filter based on the interleaved buck switch cell has been explained.
- “Shoot through” phenomenon and effect of dead time in compensation performance was explained.
- Detailed operation principle and control methods of different topologies i.e. full bridge and half bridge APF-IBC is given.
- Comparison between half cycle modulated current control and conventional current control is done.
- Interleaved structure is applied to three-phase and three-phase four wire system. Detailed operation of three-phase and three phase four wire system is given with analysis of current control strategy and harmonic detection procedure.
- Two harmonic detection method i.e. *p-q* and i_d-i_q method were implemented in both three-phase and three-phase four wire APF-IBC

By using MATLAB/SIMULINK following simulation were done

- Simulations were done with half bridge, full bridge, three-phase, three-phase four wire interleaved topologies and it has been found that these are feasible in active power filter application.

- "Shoot through" phenomenon was shown in case of both single phase and three phase active power filter.
- Effect of dead time is shown with 2 µsec and 4 µsec value of dead time on the compensating performance in simulation results.
- Simulation results show the performance of active power filter in case of i_d-i_q method is more efficient than the p-q method.
- Dc-link voltage is constant in every case but the ripple content is more in case of three phases and three phase four wire configurations with p-q method of harmonic detection.
- THD value is reduced in each case from the IEEE standard value.

From the above project work it has been found that

- Interleaved structure eliminates "shoot through" phenomena without adding dead time.
- The application of interleaved structure in active power filter results in better compensation, high reliability, efficiency and performance.
- Compensating performance of active power filter in case of i_d-i_q method is more efficient than the p-q method.

6.2 Scope for future work

- Interleaved buck converter control can be implemented in various cascade topologies which will help to construct large power equipment with less power rating.
- The control strategy can be improved by applying fuzzy control.

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